An Ultrasonic C-Scan System to Identify Damages in Impacted Fibre - Composite Plates

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Certificate

It is certified that the work contained in the thesis entitled AN ULTRASONIC C-SCAN SYSTEM TO IDENTIFY DAMAGES IN IMPACTED FIBRE-COMPOSITE PLATES, by C V Venkatesh, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

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ABSTRACT

Non Destructive Testing (NDT) play a major role in meeting the increasing demands on quality control and safety standards, product reliability, in industries like aircraft, nuclear and power generation. Fibre reinforced composite materials offer enormous potential for use in a wide number of engineering applications. The superior stiffness and strength properties of long fibre composites can be utilized to manufacture complex components with lower weights at reduced costs. The emergence of the science of fracture mechanics, together with the concepts of acceptable flaws and of total life-cycle costing, had a major influence on NDT, particularly in emphasizing the need for accurate, quantitative defect sizing. The future of NDT lies in the development of sophisticated computer pattern recognition and data processing techniques for defect characterization and quantification. Ultrasonic inspection has proved to be an effective means to evaluate the non homogeneous and anisotropic composite materials.

In the present work, a microcomputer based ultrasonic inspection system is developed by interfacing the available scanning setup with a PC-AT. An analog to digital converter card is used to digitize and transfer the ultrasonic signal to the PC. Cluster analysis is used for the post processing of data collected. Peak amplitude and the frequency components of the received ultrasonic signal are used for C-scan imaging of the impact damaged composite material specimens. The two

dimensional flaw image are displayed on the colour monitor to identify the damage zone.

The impact damaged composite laminates made of Glass/epoxy and Graphite/epoxy were scanned in the present setup. The C-scan image shows more damage areas than those that can be identified by visual inspection. Definite patterns are seen in the damage zone.

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C.V. Venkatesh

Dedication

To my grandfather

and my parents

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Chapter 1

INTRODUCTION

1.1 GENERAL INTRODUCTION

Present trend towards improved quality and safety standards, particularly in the aircraft, nuclear and power generation industries are placing increasing demands on quality control and nondestructive examination. Non-destructive testing (NDT), traditionally an end-of-line inspection tool, is beginning to be used as a quality monitoring technique both in product design and process control. This has led NDT engineers to place increasing emphasis on automated on-line systems capable of reproducible operation at higher and in more severe environments, often under computer control. The emergence of the science of fracture mechanics, together with the concepts of acceptable flaws and of total life-cycle costing, have also had a major influence on the philosophy of NDT, particularly in emphasizing the need for accurate, quantitative defect sizing. It is probably in the development of sophisticated computer pattern recognition and data processing techniques for defect characterization and quantification that the future of NDT lies, rather than in improvements in fundamental techniques of acoustics, radiography and magnetics.

The term *Non-destructive testing*, or NDT, can be applied to any inspection or test procedure which is non-intrusive and which does not damage the object being tested. It can thus encompass such diverse techniques as visual inspection with the naked eye, condition monitoring of machinery, and the functional testing of electronic components. Generally, however, the term is restricted to methods for determining the mechanical or structural integrity of engineering parts or assemblies by carrying out some test involving the use of electromagnetic radiation or acoustics, or methods enhancing visual examination by the use of fluorescent dyes or magnetic powders.

The most common use of NDT is to detect defects such as cracks, voids, or porosity, but other applications include material sorting, thickness measurement, and surface condition monitoring. The basic technologies of NDT divide broadly into those using acoustics, magnetism or electromagnetism, and radiographic techniques. Acoustic techniques include ultrasonics and acoustic emission, magnetic methods include eddy current, flux leakage and magnetic particle inspection, while radiography can embrace X-rays, gamma- and neutron radiography, as well as "fringe" techniques such as positron annihilation. NDT methods falling outside these categories include dye-penetrants, potential drop and thermography.

Of the technologies commonly associated with non-destructive testing, ultrasonics is one of the most widely used, with the possible exception of radiography, is probably the area which has received most attention in terms of research and development. It has the merits of being applicable online in real time, of enabling localized regions of a specimen to be examined in detail with relative ease, and of enabling regions at considerable depths below the surface of the test object to be inspected. Using modern techniques, the defects may be located with accuracy and their size, shape and severity quantified.

Fibre reinforced composite materials offer enormous potential for use in a wide number of engineering applications, ranging from sports goods to advanced aircraft structures. The superior stiffness and strength properties of long fibre composites can be utilized to manufacture complex components with lower weight at reduced cost. Composites are complex materials exhibiting distinct anisotropic properties. Fundamentally a composite can be considered as two or more distinct constituent materials or phases combined on a macroscopic scale. It consists of one or more discontinuous phases embedded in a continuous phase. The continuous phase is called the matrix and the discontinuous phase is called the reinforcement. Composite materials are attractive materials for their high ratio of strength and modulus to weight. Unlike metals, composite materials are generally multilayered, heterogeneous, and anisotropic. On macroscopic scales under certain conditions it can be treated as homogenous material.

The area of response of fibre composite materials to dynamic loading, particularly impact loading is of great concern. These damages are caused by low velocity, low energy impact with objects such as that resulting from a dropped tool or runway stones and hail, bird hits etc.; such impacts can produce large areas of delamination, fibre fracture and matrix cracking. Innocuous though this damage may seem, it can result in premature catastrophic failure. The fracture modes may interact under post impact loading conditions resulting in a complex fracture process. The impact damages can be accessed by several methods.

In contrast with the nondestructive evaluation of homogenous materials, where the major problem of interest is the detection, location, orienting and sizing of cracks, nondestructive evaluation of composite materials attempt to detect a variety of damage modes in a composite material. The focus of the research is helping to identify damage mechanisms in composite materials and to characterize the role

played by these damage mechanisms in the final failure process. The damage in composite materials are of many types such as fibre breaks, matrix plasticity, cracks, voids, matrix rich areas, delamination, debonding etc. Thus the questions for the nondesructive practitioner in composite materials are *Can we find damage?* and *What is the minimum size of damage that can be detected?* The first question one first must ask oneself what is that one wishes to find. The second question is how this particular knowledge is going to be useful in design or prediction of material serviceability. The first question indeed be addressed, as presently much is known about the type of damage modes and manufacturing flaws that may exist in a composite laminate.

Ultrasonic methods are the most commonly applied NDT techniques because of the relative ease of their use, and the relative amount of information that can be obtained from them. The major difficulty with the NDT of composite materials is that, unless highly refined imaging methods are used, the information obtained from a test does not provide details on the microstructure or morphology of the damage. Ultrasonic C-scanning is an important method in the process of damage identification.

1.2 STATE OF THE ART

One of the earlier studies using ultrasonic attenuation measurement for fibre reinforced composite materials was reported by Tauchert and Hsu [1]. They studied the response of glass-fibre reinforced unidirectional and cross-plied laminates. Ultrasonic waves were propagated through the thickness of the specimen while the specimen was under load in the testing frame. Attenuation was measured by comparing the amplitude of the received pulse with a standard voltage provided by

the electronic instrumentation. They noted a dependance of the attenuation with the frequency. The change in attenuation under tensile load was greater for higher frequencies than for lower ones. Williams and Doll [2] found the attenuation to be frequency dependent, both initially and intermediate stages during the fatigue test. The group velocity was frequency independent. They used through-transmission method. Williams and Lampert [3] used the same technique as Williams and Doll to show a correlation between the the number of drop weight impacts applied to graphite/epoxy laminates, the residual tensile strength and the through-the-thickness ultrasonic attenuation. They conclude that their results strongly suggested that impact damage in graphite fibre composite materials can be non-destructively assessed quantitatively using through-the-thickness attenuation measurement.

The detection of voids in reinforced plastic composite materials has attracted some attention in the literature because of the important role played by the presence of the voids on the interlaminar shear strength of composite laminates. Stone and Clarke [4] observed that the main factors influencing the observed ultrasonic attenuation in a scanned specimen are: surface texture; the presence of voids; delaminations; the state of cure of the resin; the fibre volume fraction; and the condition of the fibre-matrix interface. Attenuation caused by delaminations is relatively easy to distinguish from that caused by voids when the A-scan presentation of the ultrasonic signal is observed, because a delamination will produce a separate echo in pulse echo mode between observed times of the front and back surface reflections. In through-transmission, the delamination will totally blank out the signal if it is larger than the size of the ultrasonic beam. It is difficult to separate the effect of the state of cure of the resin from that of the voids because incorrect cure will also result in voids. They also observed that fibre volume fraction did not appear to have a very strong affect on attenuation.

Of the many nondestructive techniques used to characterize composite materials, the most often applied one, is the ultrasonic C-scanning. Ultrasonic C-scanning was originally developed for application to homogeneous materials. Historically, ultrasonic investigators have used the terminology A-, B-, or C-scan to describe the type of presentation used in developing information from the data taken during the ultrasonic study of a material specimen. An ultrasonic A-scan is the most familiar form of data presentation and is the basis for the other two types of scans as well, in that an A-scan is almost always used in setting up the test and establishing the test parameters. An ultrasonic A-scan refers to data presented as signal amplitude versus time. B-scan is the presentation of ultrasonic data in the form of a depth profile versus position along a specimen. A C-scan is the presentation of the plan view of the ultrasonic attenuation of the examined specimen. Two transducers can be used in a pitch-catch mode on opposite sides of the specimen, or a single transducer can be used in pulse-echo from one side of the specimen. Pulse-echo is most often used in any case when the attenuation is low enough to capture a meaningful signal after propagating twice through the specimen. Any differences in quality of the specimen that may further attenuate the signal or scatter will be detectable by a change in amplitude of the detected echo.

Application of an ultrasonic C-scan to the investigation of composite materials is given by Martin[5]. He used a number of metal matrix composite materials in his test program. Hagemaier and his group [6, 7] concluded that ultrasonics can be used to reveal debonds, delaminations, porosity, and resin content, as well as for thickness gauging and, under controlled conditions, to provide a correlation between physical and mechanical properties. Mool and Stephenson [8] used ultrasonic C-scan with through-transmission technique to scan specimens manufactured with known defects. They observed that complete loss of a through-transmission signal was typical of a delamination. Ultrasonic C-scanning has also been used to study

damage initiation and development in composite materials as a result of mechanical loadings, such as fatigue loadings by Nevadunsky, Salkind, Strutgeon [25, 26].

In recent years, attention has been given to the development of real time or automated ultrasonic C-scanning through the use of computers. Mahoon [9] have discussed how British Aerospace have overcome difficulties associated with normal C-scanning by recording digitized ultrasonic C-scan data in a computer. The requirement for trained nondestructive personnel is eliminated. The sub critical information is automatically available. J.M.Carson and J.L.Rose [10] have discussed in their paper typical test procedures for the collection and processing of ultrasonic signals. They have collected averaged RF signal and its fourier transform . They have also used pattern recognition techniques for the analysis of the data. Jones[11] developed the Automatic Ultrasonic Scanning System (AUSS). The received ultrasonic signal is digitized and analyzed by the computer so as to provide a 15-shade, gray scale level. Jones concluded that the AUSS approach to automated ultrasonic data collection, processing and display was proven to be very effective and efficient in inspecting composite materials.

Williams and Lee [12] have discussed some of the results on the ultrasonic NDE of composite materials based on their research in the composite materials and NDE laboratory at MIT. The have reported ultrasonic frequency spectrum as a potentially useful NDE characteristic. Ultrasonic C-scanning methods have been used by several researchers for the identification of impact damage. Cantwell and Morton[13] have reported in their paper that damages can be clearly seen in C-scan images of peak amplitudes.

Rose, Nestlertoh and Balasubrmanyan [14, 15] in their paper have stressed the need for feature mapping. The have reported that detection of most anomalies in materials can be performed by a classical B- or C-scan inspection of the struc-

ture. To identify the particular anomaly type, however, more information must be extracted from an ultrasonic signal. The basic hypothesis of a feature mapping (F-map) system is that each anomaly type will interact with an ultrasonic wave in a unique way. These variations must be detected. Data acquisition methodology is extremely important in providing an opportunity for physics and mechanics to play an important role in feature selection. A subset of F-scanning is the traditional C-scanning, which uses the peak amplitude in a gate as feature value, to generate an image. Features can be extracted from time and frequency domains and in deriving the relevant features, special attention is paid to the digital signal processing computational requirements of the fast fourier transforms (FFTs), to obtain frequency response.

1.3 PRESENT WORK

The present work is an attempt to develop an automated ultrasonic scanning system to obtain C-scan images to identify damages in impact damaged fibre composite materials. This work is further modification and improvement of the works of Shukla [16] and Mahajan [17] of this laboratory. An attempt has been made to develop a comprehensive procedure to record the complete signal and do extensive post processing of the data. The A-scan data was recorded in real time during scanning by interfacing a microcomputer with the ultrasonic flaw detector. The complete analog signal of the flaw detector were digitized using a very high speed A/D converter. The online Fourier Transformation of the data (FFT) is performed and the frequency components are recorded. An extensive statistical analysis (post processing) of the data has been done using cluster analysis to identify damages in impact damaged composite plates (Glass/Epoxy and Graphite/Epoxy). The plotted images show clear damage representation using the higher harmonics.

Details concerning principle of ultrasonic methods are discussed in chapter 2. A typical scanning system consists of an X-Y scanner tank, probes, ultrasonic flaw detector, stepper motors, controller card for the motors, A/D (analog to digital) card, microcomputer.

Chapter 2

BASICS OF ULTRASONIC TECHNIQUES IN NDE

The term ultrasonics is used to describe mechanical waves propagated in gases, liquids and solids at frequencies above the upper limit of human hearing — above 20 KHz and upto 400 MHz. Because the characteristics of these waves are influenced by the mechanical properties of any medium through which they pass, one can use ultrasonics to investigate the properties of the medium.

In ultrasonic testing pulsed waves are used. The pulses can be rectangular or exponential in shape. Conventional ultrasonic inspection systems use transducers which must be coupled to the test specimen either through physical contact or by the provision of coupling fluid, generally water, which provides a medium for the sound waves. The name transducer is given to a device which enables the transformation of energy from one form to another.

2.1 THE NATURE OF WAVE MOTION

When ultrasonic waves pass through a medium, They are classified according to the geometry of the medium through which the wave is propagating. Thus, *bulk waves* are waves that propagate through a medium which is so large in size compared to the wavelength of the medium so that the medium can be considered to be of infinite in size. In this instance, the interaction of the wave with boundaries of the material does not affect the major character of the wave propagation. Bulk waves in solids are normally described as being longitudinal (or compressional) when the particle displacements caused at a point by the wave as it passes are parallel to the direction in which the wave is propagating. A transverse wave is a wave in which particle motion is perpendicular to the direction in which the wave is propagating. Ultrasonic inspection in most cases is conducted using bulk type waves or quasi bulk waves.

The study of wave propagation in composite materials is complicated by three factors:

1. composite materials are anisotropic;
2. composite materials are heterogeneous;
3. most often, the composite specimens are used as in the form of thin plate.

If the wavelengths are large compared with the size of the fibers, as a first approximation, one can assume the composite material to be homogeneous. This is the basic assumption which is used predominantly for composite laminate theory [18, 19], and is also used to explain many of the basic observations made in interpreting ultrasonic wave propagation in composite materials.

2.2 TRANSDUCERS

Certain materials, when placed in an electric field, exhibit mechanical deformation. Conversely, these materials, when deformed, produce electric charges at their surfaces. This phenomenon, known as piezoelectricity, forms the basis of the design and construction of wide range of transducers used for ultrasonic testing. Two main types of transducer used for ultrasonic testing are quartz and ceramic oscillators.

In many applications, particularly when examining complex specimens for small defects, a focussed transducer, capable of concentrating ultrasound on a small target area, may be achieved by the use of a lens fixed to the front face of the transducer disc, or by suitably shaping the disc itself.

2.3 ULTRASONIC TESTING METHODS

The testing process using ultrasonic instruments is generally carried out either using *Pulse Echo Method or Through Transmission Method.*

2.3.1 Pulse Echo Method

The apparatus (fig.2.1) consists of a pulse generator which generates an electric pulse of sine waves that excite the transducer, fitted to the transmitting probe. Ultrasonic waves then propagate as pulses in the material under test. The presence of a defect will cause some of the energy to be reflected and return to the transducer. The transducer for collecting the reflected waves may be the one which is sending the signals or a separate one as in pitch catch method. Those waves which bypass the defect are reflected from the opposite surface of the material and reach the receiving transducer at a later time. The image corresponding to this on the oscilloscope

screen is called bottom echo or back wall echo.

To use this method, two basic requirements are necessary. First, the material must be thick enough, in comparison with the minimum pulse width that can be generated by the available ultrasonic instrumentation, so that echoes can be distinctly discriminated in time. The attenuation must be low enough to allow for the detection of atleast two echoes of sufficient height to be above noise level. Many composite materials are relatively thin and are of the order of $1-3$ MM ($8-16$ plies) thick. The velocity of longitudinal waves perpendicular to the laminate plane (i.e. the plane of fibers) is of the order of $5-6 \times 10^6$ MM per second. Hence the time to travel through the thickness and return to the surface in a pulse-echo arrangement is only $0.2 - 0.6$ microseconds. The attenuation of ultrasonic waves is relatively high in composite materials. The main advantage of this method of inspection is that access is necessary only from one side of the sample; (this is important when only one surface is accessible). The sensitivity is high in this method as the wave contains more information as it travels twice through the thickness of the specimen.

2.3.2 Through Transmission Method

For this method ultrasonic waves enter the test object on one side and are picked up by another transducer after emerging from the other side. Any discontinuity in the path of the beam gives rise to reflection, with the result that there is a decrease in the intensity of the transmitted waves (fig.2.2). A decided disadvantage of the transmission method with respect to the pulse echo method is that two opposite surfaces of the test material must be accessible; also the axes of the probes must be exactly aligned so that they are opposite to one another. Unless a suitable jig is made, the method is difficult to carry out. An advantage of the transmission method is that it is suitable for thin sheets of materials also.

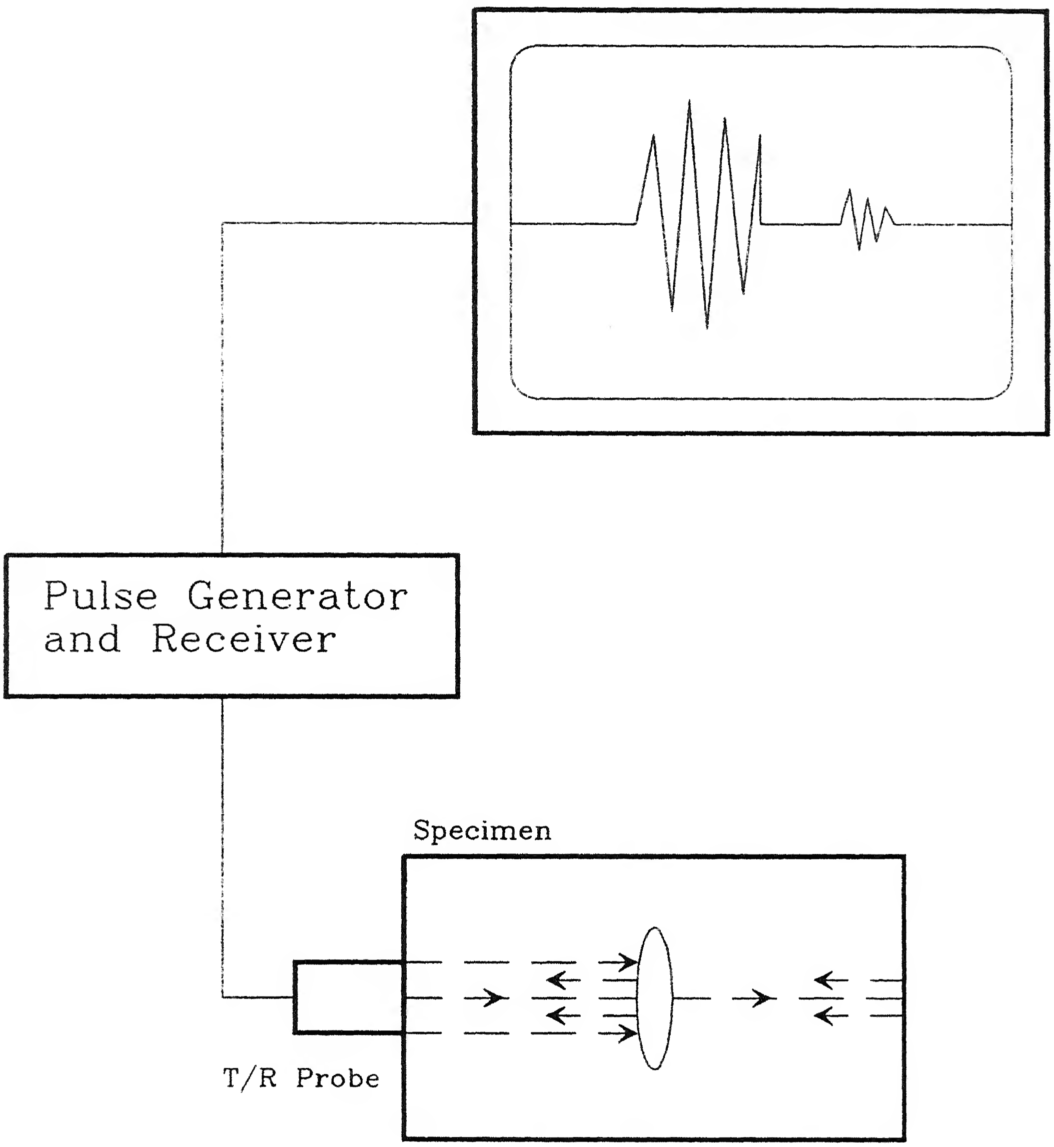

Figure 2.1: Schematic Diagram for
Pulse Echo Technique

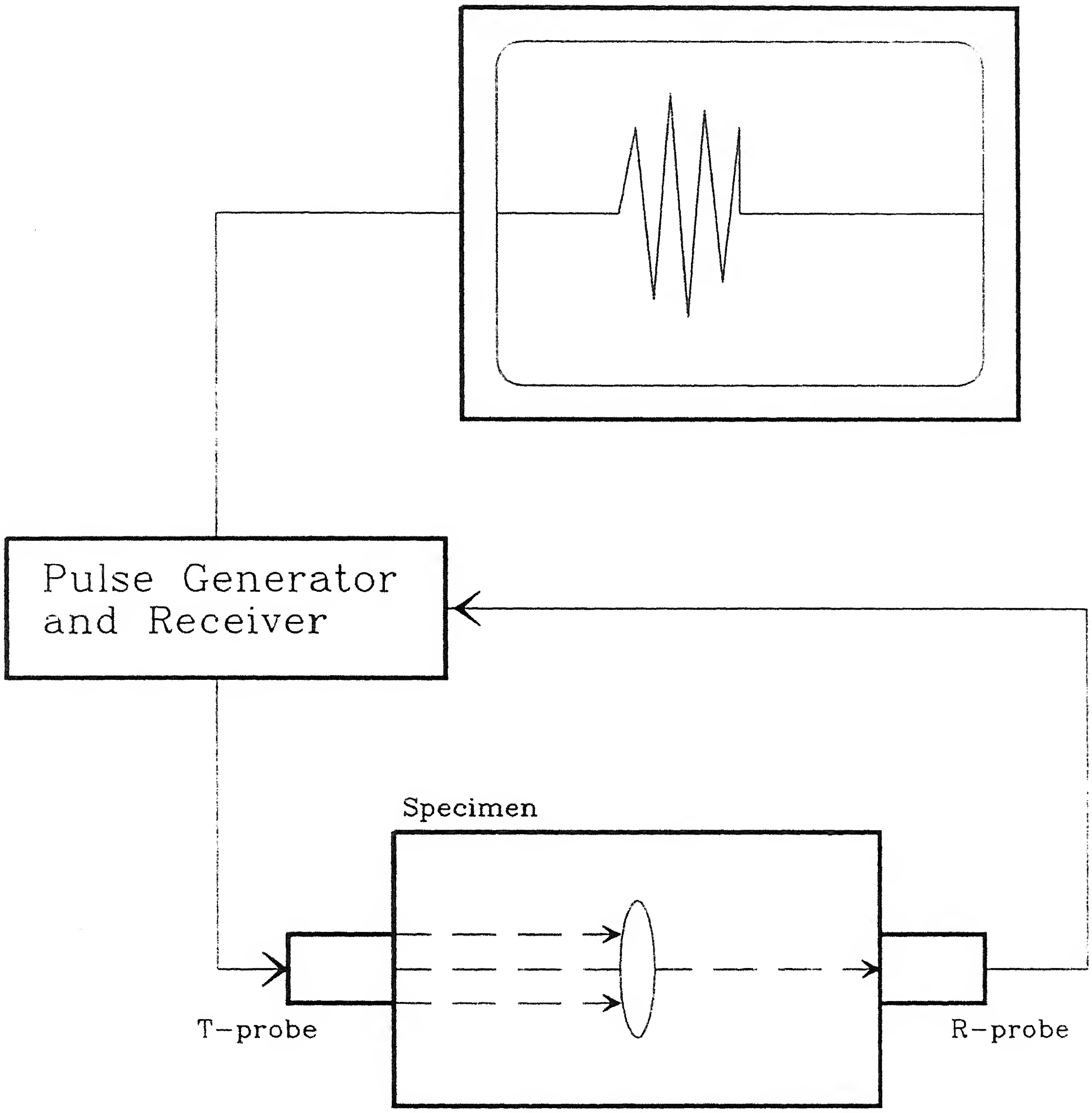

Figure 2.2: Schematic Diagram for
Through Transmission Technique

Chapter 3

EXPERIMENTAL SETUP AND DATA COLLECTION

This chapter describes the details of the experimental setup to, collect the signal, digitize and post process the data. The main aim of the present work was to design a comprehensive system to digitize the signal from the ultrasonic scanner and to obtain C-scan automatically. With automation of the process the need for skilled people can be eliminated.As the ultrasonic signal contains information regarding the material a means to collect and store the complete signal is necessary to do post processing such as signal processing, image processing, etc.

In the present work, Software was developed for the precise movement of the probes by stepper motors and for acquiring the data was developed. The A/D card was interfaced with a PC-AT 386 SX machine to digitize the ultrasonic signal and collect the waveform at a high sampling rate. The experimental setup and a brief general procedure for experiment and data acquisition is described in the subsequent sections.

The analysis is done for the scanned data obtained from impacted Glass/epoxy

and Graphite/epoxy composite laminates. Cluster analysis has been employed as the tool for the statistical analysis of data obtained. Details of the analysis and post processing are presented in chapter 4. The results obtained after using the cluster analysis programs are given in chapter 5. Conclusions drawn and scope for future work have been included in chapter 6.

3.1 EXPERIMENTAL SETUP

The main objective of the experimental setup is to take an automated scan of the composite laminates.

3.1.1 Scanning Tank

The purpose of the scanning tank is to house the stepper motors, the probes and the composite specimen. To reduce the ultrasonic attenuation, probes and the plate were submerged in water. To make the setting up the scanning procedure easy and observe the side walls of the scanning tank have been fabricated using perspex. Two lead screws each of pitch $4mm$ and perpendicular to each other have been provided at the top of the tank, each of which is independently run by a separate stepper motor. The probe is mounted in a probe holder which, in turn, is mounted on the lead screw as shown in (fig.3.1). The probe can be moved very accurately as the lead screws are of zero backlash grade.In this investigation the probes were moved in steps of $1mm$.

3.1.2 Ultrasonic Flaw Detector

For generating ultrasonic waves and collecting the received signal the probes are connected to the ultrasonic flaw detector (UFD). The UFD is of Krautkramer-

Branson make (USIP 12). The generated wave by the UFD can either be used in narrow band region or broad band region depending on the type of application. The UFD can be used with a single probe for *pulse echo method* or with two identical probes for *through transmission method*. The received signal can be obtained from the UFD in Rectified (FW) or in RF (Radio Frequency) mode. The amplitude of the received signal can be adjusted accurately by finer controls to the desired level to reduce noise. The time base can be adjusted to vary the distance between the successive echoes.

3.1.3 Hardwares

A microcomputer PC-AT 386 SX (cpu 25/33 MHz, 64KB ROM, 1MB RAM expandable upto 16 MB, one 1.44MB floppy disk drive, with serial and parallel ports, 40 MB Hard Disk, VGA monochrome monitor) is interfaced with the hardware such as stepper motors, ultrasonic flaw detector, A/D converter described in the following subsection for collection and storage of data. For post processing and displaying of images a PC-AT 386 (numeric coprocessor, 4MB RAM,1.2 MB floppy drive,parallel and serial ports, 40 MB hard disk) with a colour monitor is used.

3.1.4 Stepper Motor

The stepper motors used in the present setup are of type STM 601 with 12v input. The torque capacity of the motor is 2 kg cm. The maximum step rate is 1023. The motors can be moved either in clockwise or counterclockwise direction. The motor operates by the pulses sent from the driver board. The number of clock pulses for one revolution is 200. For one revolution of the screw the probes move by 4 mm. In this work the motors are moved with 50 clock pulses at a time there by moving the motor by 1 mm. The scan is taken as illustrated in the fig.3.3.

3.1.5 Stepper Motor Control Card

The PCL-211 stepper motor control card is used to drive a stepper motor coupled to a shaft in precise increments, direction, and speeds. Very accurate repeatable movements of the motor can be achieved. With this card a maximum of 3 motors can be controlled simultaneously. Each independent stepper channel consists of a 8039 processor that can execute a set of motion control commands. Every 8039 processor also comes with an on board ROM where the control program for the processor resides. All commands sent by the PC are executed by the processor running the control program. Once the command is sent, the PC is set free from controlling the particular motion desired. Thus optimum utilisation of PC resources is possible.

3.1.6 Analog To Digital Converter

Using a A/D converter the received RF signals from UFD is digitized. In this investigation a SONOTEK STR* 8100 A/D card is used. The card is capable of digitizing the RF signals with a maximum sampling rate of 100 MHz and maximum data acquisition flexibility through a 64K, on-board high speed memory buffer. All board functions are under software control including input channel selection, AC/DC coupling, input voltage range, RF/Video, sampling rates, a/d output coding, trigger selection, clock control, threshold phase and level, board selection and interrupt enabling. Industry standard BNC connectors are used to provide easy setup while maintaining maximum signal integrity. The board's high speed data acquisition memory is mapped directly into PC memory space. Once the waveform has been captured, the PC can transfer data off the board at 1.5 MHz rate (8 bit) or 3 MHz rate (16 bit) using simple memory block instructions. This board provides freedom from the static architecture of a stand alone instrument and the computer. The

D100A Digital Oscilloscope Program supplied by the manufacturers of the board is used to choose the appropriate parameters.

In the present setup the A/D card is installed outside the PC system unit as this requires higher power and this card can be switched on only when the data acquisition is needed. This is done using the PCX-795 PC XT/AT bus expansion system. The PCX-795 includes one PCX-795M master card that can be installed within a PC XT/AT, and one PCX-795S slave card that can be plugged into the system unit as an outside expansion, and the cables to link these cards together. This card has on-board $1, 2, 4, 8, 16$, and 32 wait state generation, switch setting for MEMORY bank selection, switch setting for I/O selection and switch setting for DMA channel selection.

3.1.7 Transducers

The transducers (probes) used in the present investigation are ENM4L, ENM10L and EI6B generates 4 MHz, 10 MHz and 6 MHz broad band. These are transducers which generate longitudinal waves. The diameter of the transducers is $10MM$. They are connected to the UFD by water proof connectors. The fixtures were fabricated to hold the transducers in vertical position.

3.2 SOFTWARES DEVELOPED

The following softwares have been developed in the present investigation for the collection of data.

1. For the precise motion of stepper motors, (MOTOR.C)

2. For the collection of full wave data and the attenuations, (SCAN.C)

3.3 EXPERIMENTAL PROCEDURE

The specimen to be investigated is cleaned and the area under investigation is marked. Bring the probe by moving the motor to the start position as shown in fig.3.3. It was ensured that probe and specimen were all submerged in water. Move the probe holder down so that the probe dips in water. Adjust the distance between the probe surface and the top surface of the specimen so as to distinctly observe the initial burst and the reflected signal on the UFD oscilloscope screen. However, the distance between the top and bottom surface echo on the time scale depends on the thickness of the specimen being investigated. The RF signals from the UFD is examined on the software digital oscilloscope provided along with the A/D card (*i.e.* *D100A.EXE*). The gate parameters on the desired signal to be digitized is noted and corresponding changes were made in the *SETUP.STR* file.

Once the initial settings are done the scanning of the specimen can be started by running a master control program. The flow diagram for the master control program is as shown in fig.3.4. The scanning distance between two successive points in the Y direction can be varied by specifying the required distance as the input for the subroutine of motor in Y direction. Similarly the distance between two successive lines can also be varied by specifying the distance in the subroutine for the motor in X direction refer to fig.fig:pmi. In the present investigation both the distances have been kept as $1mm$. Run the scanning program. The data collected are stored in the files in append mode so that the scanning can be interrupted if desired. If interrupted, to restart, run the scanning program again and give the coordinates of the last scanned point when asked for. The peak amplitude after averaging for removal of time dependent noises and the coordinates are stored in a file. The peak detection is done by software. The averaged amplitudes of different harmonics, obtained after performing FFT on the received signal, is stored in a different file

which is the input file for further processing in *cluster analysis*.

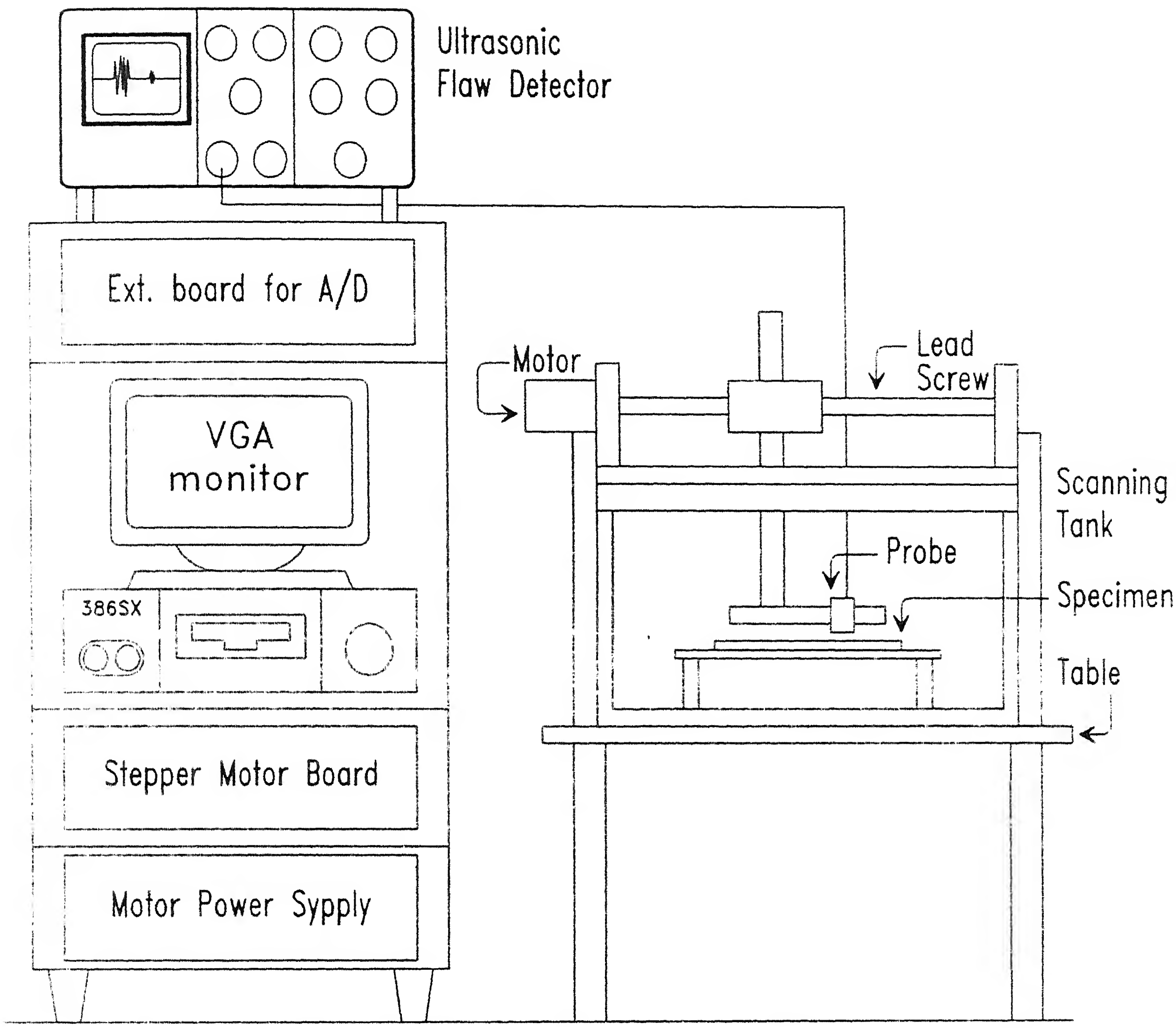

Figure 3.1: Schematic Diagram of Automated Ultrasonic Scanning System

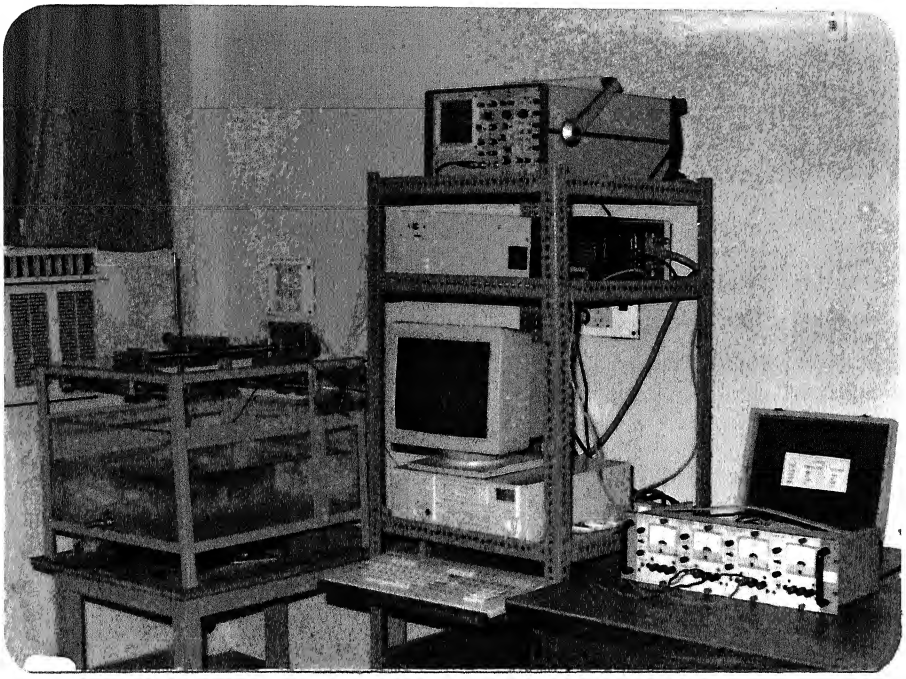

Figure 3.2: Automated Ultrasonic Scanning System

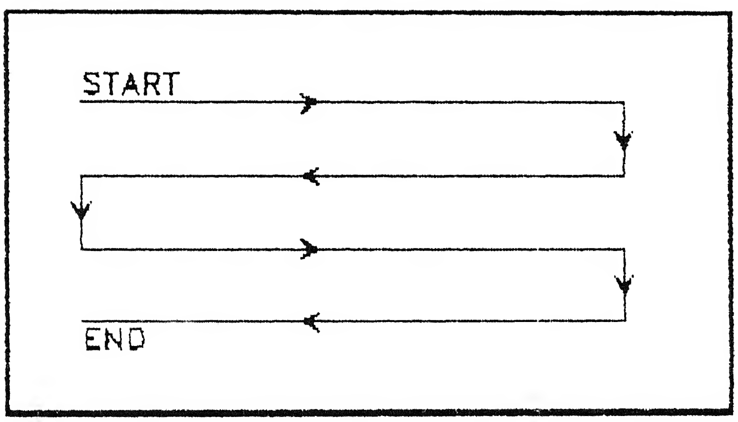

Figure 3.3: Probe Movement Illustration

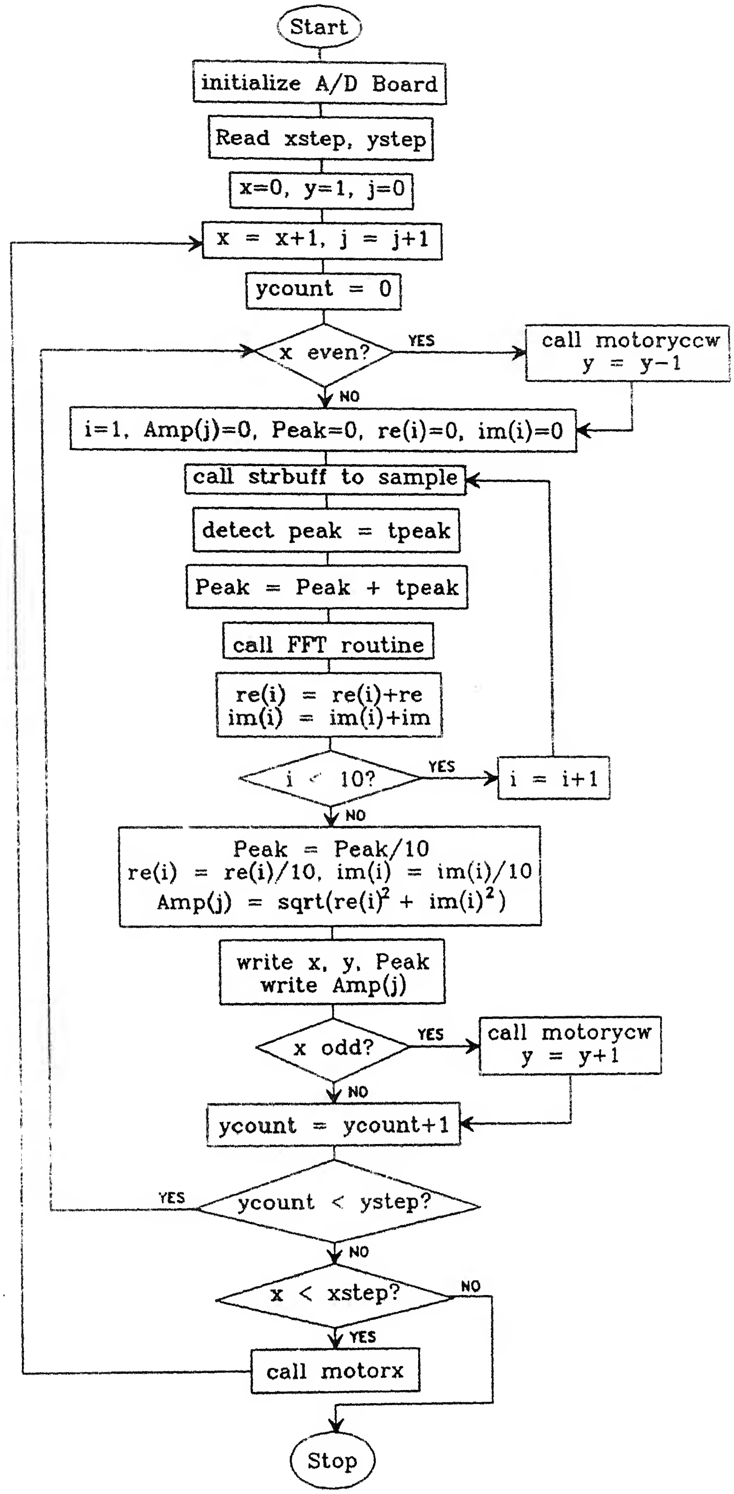

Figure 3.4: Flow Diagram for Master Control Program

Chapter 4

CLUSTER ANALYSIS AND POST PROCESSING

As has been mentioned earlier impact damaged composite plates undergo many damages such as delamination, debonding, fibre fracture, matrix cracking etc. Because of the variation in the geometry of the flaw, heterogeneity of the composite material and instability of the signal, there is statistical variation of the signal. To identify the particular damage type the specific information must be extracted from the signal. The feature should contain the information that correlates with shape, size and orientation. A feature mapping system was designed to obtain this information. The basic hypothesis of a feature mapping (F-map) system is that each damage type will interact with an ultrasonic wave in a unique way. These variations must be detected and quantified into features and then used in the identification procedure. Physically based features include, for example rise time, pulse duration, fall time or features from transfer function domain etc. A decision algorithm is developed using cluster analysis, discriminant functions etc. The final step in the post processing is a map showing the damage type at a given position.

4.1 BASICS OF CLUSTER ANALYSIS

Classification is an act or process of assigning a new item or observation to its proper place in an established set of categories. In cluster analysis, little or nothing is known about the category structure. All that available is a collection of observations whose category memberships are unknown. The operational objective in this case is to sort the observations into groups such that the degree of natural association is high among members of the same group and low between members of different groups. Cluster analysis has been employed in a great variety of applications, as an effective tool in scientific inquiry such as life sciences, earth sciences, medicine, engineering sciences etc. Bow [20] defines clustering a non supervised classification of objects. Thus for a given data set D of N events $(x_1, x_2, \ldots, x_n)$, to be classified into K clusters, the process of clustering can be formally stated as: to seek the clusters $c_1, c_2, \ldots, c_k$, such that every x_i, $i = 1, 2, ...N$, fall into one of these clusters and no x_i falls in two region.

Mathematically,

$$\begin{aligned} c_1 \cup c_2 \cup \cdots c_k &= D, \\ c_i \cap c_j &= 0 i \neq j. \end{aligned}$$

4.2 STEPS OF CLUSTER ANALYSIS

A detailed discussion is devoted of all the choices of clustering a set of data is listed by Anderberg [21] all of which can shape the outcome profoundly. These are briefly explained with reference to the present work.

4.2.1 Choice of Data Units

When applying clustering analysis one should be clear regarding the objects for analysis. This could be persons, animals, opinions, commodities, or other such entities. In the present work the objects for analysis were the scanned attenuations and frequency components.

4.2.2 Choice of Variables

It has the greatest influence on the ultimate results of cluster analysis. The data units cannot be merely arrayed for study. They must be described in terms of their characteristics, class memberships, traits and such other properties. The variables chosen for the study are the frequency components of the reflected ultrasonic wave from the impact damaged fibre composite plates.

The discussion up to this point deal with the clustering of data units as described by variables. J.L.Rose J.B.Nestlertoh and K.Balasubrmanyan [14, 15] in their paper have stressed on the need for feature mapping. They have reported that detection of most anomalies can be performed by a classical B- Or C-scan inspection of the structure using peak amplitude plots. To identify the particular damage type, however, more information must be extracted from an ultrasonic signal. The basic hypothesis of a feature mapping (F-map) system is that each anomaly type will interact with an ultrasonic wave in a unique way. A subset of F-scanning is the traditional C-scanning, which uses a particular feature value, the peak amplitude in a gate, to generate an image. Features can be extracted from time and frequency domains and in deriving the relevant features, special attention is paid to the digital signal processing computational requirements of the fast fourier transforms (FFTs), to obtain harmonics. Hence in the present work each frequency component (harmonic) is separately treated as a variable.

4.2.3 Homogenizing Variables

Lack of homogeneity pose a problem with real data sets. In measuring association among variables different types of scales create problems. To overcome this difficulty all the variables were normalized using linear interpolation.

4.2.4 Similarity Measures

Most cluster analysis methods require a measure of similarity to be defined for every pairwise combination of the entities to be clustered. The similarity measure is usually given in numerical form to indicate the degree of natural association/resemblance between events in a data set. When clustering data units the proximity of individuals is usually expressed as a distance. Two commonly used distances are the Euclidean distance defined as:

$$d(\vec{x},\vec{y}) = (\sum_{i=1}^{m} |x_i - y_i|^2)^{\frac{1}{2}} \tag{4.1}$$

and the city block distance defined as :

$$d(\vec{x},\vec{y}) = \sum_{i=1}^{m} |x_i - y_i| \tag{4.2}$$

where, $\vec{x} = [x_1 \ x_2 \ \ldots \ x_m]^T$, $\vec{y} = [y_1 \ y_2 \ \ldots \ y_m]^T$, m= number of events. Euclidean distance has been used as the similarity measure in the present analysis.

4.2.5 Clustering Criterion

Generally, one thinks of the term *cluster* as a set of objects which are all close. But when it comes to finding clusters in real data, the term must bear a definite meaning. It may not be possible to say what a cluster is in abstract terms, but it can always be defined constructively through statement of the criterion and an implementing

algorithm. In the present analysis,the algorithm starts with the maximum number of possible clusters and converges to the desired number of clusters.

4.2.6 Algorithm and Implementation

Even after choosing data units, variables, transformations, similarity measure, and a criterion, there still remains the problem of actually generating clusters. The choice of algorithm decides the means of implementation. Hierarchal clustering methods were chosen for the present analysis for the advantages cited in the subsequent section.

4.2.7 Interpretation of Results

The clusters obtained are summary descriptive statistics much like the mean and variance. For a given similarity measure, criterion and algorithm the production of clusters can be a straight forward mechanical procedure. But the whole focus of the clustering criterion and algorithm is to give a set of clusters that are well differentiated from each other. Even the analyst has got a role to play. The value of exploratory cluster analysis lies in suggested relationships and principles that were previously unnoticed. It is conditioned by three essential elements: the context of the problem, the analysts knowledge of the context and the analysts research objectives.

The context of the problem includes virtually everything that may influence the observation or interpretation of the data. The most pertinent aspect of context include the actual circumstances of data collection, related facts and theory. Also, the analysts knowledge and understanding of the problem context has long been recognized as an important element of all scientific inquiry. Even the analysts

research objectives may change the face of entire investigation. Though a solution is sought with many objectives in mind, the ideal solution is the one which dominates, all other alternatives. Thus, context and objectives interact in cluster analysis, the later adjusting to accommodate a new appreciation of the former.

4.3 CLUSTERING METHODS

Clustering methods could be either hierarchical or nonhierarchical. In hierarchical clustering, the sequence of forming clusters proceeds in such a way that whenever two samples are put into one cluster at some stage, they remain together at all subsequent levels. In the nonhierarchical method, some initial points are selected and the cluster memberships are altered with respect to certain criterion, before the final clusters are obtained.

4.3.1 Hierarchical Clustering Method

Hierarchical methods are broadly divided into two types: *agglomerative* and *divisive*. In the agglomerative procedure, each of the event is treated as a separate cluster in the beginning. The number of clusters are reduced by merging most similar pairs iteratively using a similarity measure till only one cluster remains or the desired number of clusters are obtained. If we call each of the events as a branch and the entire data set as a root, then, agglomerative methods can be described as clustering methods which build the tree from the root. Less common are the divisive hierarchical methods, which begin at the root and work towards the branches. That is, the procedure begins by treating the entire data set as one cluster. This cluster is divided into two clusters using a similarity measure and the procedure is repeated till a suitable stopping criterion is satisfied.

Computer code developed by D.Ravikumar [22] are used in the present analysis for clustering. These codes have been modified to suit the present analysis. The scanned data are input to this code which generates an output plot file for the data set. The flow chart for this purpose is as shown in (fig.4.1). Plot file contains the coordinates of a point and the cluster number to which the data at the particular coordinate belongs to. This file is plotted to show the different groups with different colours.

4.3.2 Nonhierarchical Clustering Method

In nonhierarchical clustering, for a given matrix of I events on J variables, the events are allocated to N clusters in such a way that the within cluster sum of squares of deviations from their respective means is minimized. The primary inputs are: matrix of observations, the number of clusters, and the initial cluster centres. Selection of initial seed points or cluster centers is an important step in this method. The method suggested by Ball and Hall [23] offers a unique set of seed points for a certain threshold distance and certain number of clusters. The principle is: take the overall mean vector of the data set as the first seed point; select subsequent seed points by examining the data units in their input sequence and accept any data unit which is atleast some specified distance, say d, from all previously chosen seed points; continue choosing seed points until N seed points are accumulated or the data set is exhausted. The threshold distance should be varied to get the required number of seed points. The variables are scaled using linear interpolation method. The thinly populated clusters can be removed and clustering process can be carried out on the modified data set.

4.3.3 Advantages and Disadvantages of Clustering Methods

The Hierarchical clustering method is straight forward and converges to the required number of clusters. The solution obtained for the particular cluster is unique. With the microcomputers which are quite fast this method can be easily adopted.

In nonhierarchical clustering an initial guess has to be made to obtain the required number of seed points. The solution is not unique. When large amount of data is processed the method poses difficulty in obtaining the required number of clusters. If the number of clusters required has to be varied the whole process of clustering is to be repeated. Also until a large number of data sets are analysed and tested the method cannot be adopted.

4.4 POST PROCESSING

The ultrasonic signals contain the information regarding the material in its path. To extract this post processing is essential. The time domain signal nevertheless provides considerable interest into the classification problem at hand. For instance, knowing the amplitude of the signal enables us to gauge the intensity or severity of the physical process or event that produce it. However an unmodified or raw signal may not extract all information from a physical process or event. For this various mathematical operations, called *Transformations* are required to be performed on the raw signal.

In almost all signal processing applications, an important transformation called *Fourier Transform* is employed. This transformation translates a time domain signal into what is known as a power domain signal. It can also be referred to as a frequency domain signal because it actually shows the power of the signal at each frequency; thus,in effect, it is a plot of power versus frequency. In this domain

classification process can considerably be improved since many phenomena occur only at a specific frequency or within a particular range of frequencies.

In a manner analogous to that employed in the time domain, the intensity of a particular mechanism is indicated by the amplitude of the peak of the frequency domain signal. In this case, however, the peak will indicate the intensity at a particular frequency rather than at one instant in time. In the cases where the phenomena of interest are spread out over a large range of frequencies the power spectrum may be divided into zones and the percentage of power in each of these zones may be used as a basis for classification.

The following softwares were developed for post processing in the present work.

1. To perform online FFT of the scanned data (SCFT.C),
2. To obtain the clustered output i.e plot files (HIPO.FOR),
3. To plot the plot files generated (DRAW.C).

In the present work the signals were collected after sampling at a rate of 100 MHz. The number of points transferred off the board on the received wave is 512. The higher the number of points transferred, the accuracy of digitization is more. Since the number of points transferred off board must be an integer power of 2 for doing FFT, 512 was selected as the number of points to be transferred, since the next higher value, which is 1024 demands a large storage and large amount of computations. The frequency of each harmonic is given by

$$f_i = \left(\frac{samplingrate}{2}\right) \times \left(\frac{1}{Numberofpointsoffboard}\right) \tag{4.3}$$

The FFT is done here to observe the effect of damages on the different frequency components. In the present work an attempt has been made to conduct a model experiment on the composite laminates. The results of the post processing have been discussed in chapter 5.

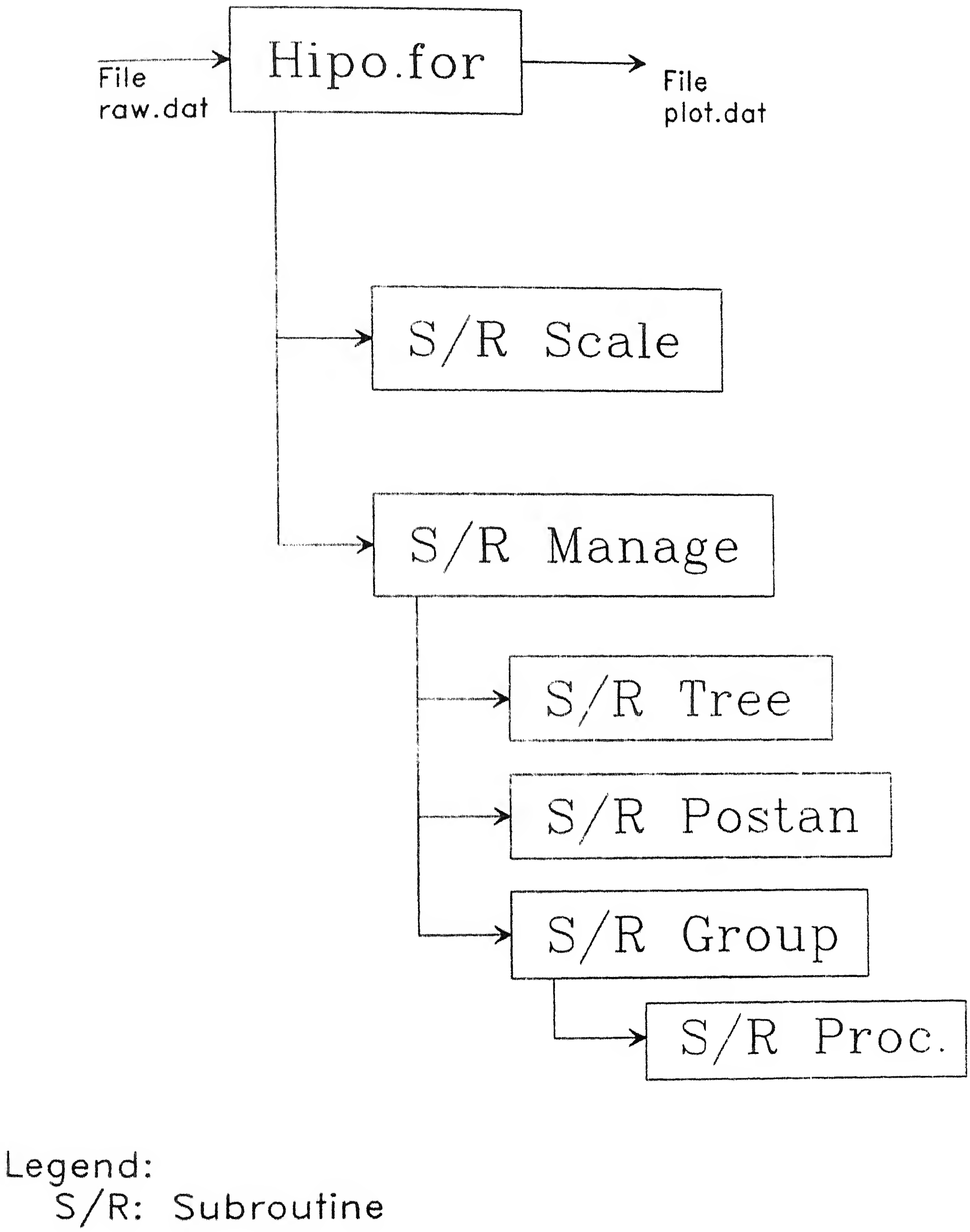

Figure 4.1: Flowchart for Hierarchical Clustering Method

Chapter 5

RESULTS AND DISCUSSIONS

5.1 SPECIMENS

The specimens used in the present investigations are impact damaged graphite/epoxy and glass/epoxy fibre composites. The specimens were prepared with hand-layup technique. [23] The glass/epoxy specimens were made from balanced glass cloth. The graphite/epoxy specimens were made from carbon cloth (G 80). The laminates were impacted by a cylindrical projectile of length 20 MM and hemi-spherical nose with velocities ranging from 41 to 58.5 M/sec.

5.2 DATA ACQUISITION

Data collection is the most important initial step in ultrasonic scanning. The effectiveness of through transmission and normal beam pulse echo techniques were investigated in the present work. More emphasis is laid on the pulse echo technique for the reasons given in chapter 2. The laminates impacted with high velocity, which have clearly visible damages, are used as samples to calibrate the system.

In the pulse echo technique echoes from the top surface and back surface can be seen. Since the laminate is very thin it is very difficult to distinguish the top and back echoes. The top surface echo in the heavily impacted plates dominates, hence the re-reflected back echo is considered for investigation. The aim is to collect signals after they have passed through the inner damaged regions. These signals are analysed to get the information on damage using Hierarchical Clustering method.

5.3 SELECTION OF NUMBER OF CLUSTERS

In Hierarchical Clustering method, the number of clusters formed that can be varied from a minimum of one to the maximum of number of events in the data set. It was observed in the process of analysis that classifying data into few clusters results in poor representation of the damage, whereas a large number of clusters leads to a situation in which it becomes difficult to recognize the patterns. The types of damages in composite materials are mainly five or six types, such as delamination, debonding, fibre fracture, matrix cracking, resin richness etc. Taking into account the possibility of a few stray clusters the total number of clusters have been limited to 10.

5.4 RESULTS OF THROUGH TRANSMISSION SCAN

A scan using through transmission technique was conducted on impact damaged Glass/Epoxy laminate using a pair of identical $6MHz$ probes. The detailed procedure for conducting the experiment is given in chapter 3. The signal collected by the receiving probe is displayed on the screen of the UFD. This signal also after

being sampled and digitized by PC is displayed by the software on the PC monitor. The necessary gate to be set on this received wave to catch the appropriate part of the echo is determined. Those values of the parameters have been set in the input file (SETUP.STR) so that the full wave on the set gate at each point was digitized and recorded. The fourier transform of the full wave were determined using FFT algorithms at each point. The magnitudes of each harmonic corresponding to all (x,y) locations is used to form a variable for clustering process.

The clustered output of peak amplitude is as shown in fig. 5.2 (P1). The plots of a few harmonics are shown in the fig. 5.3 (First row). The clustered outputs of each harmonic have been plotted in the form of a grid. Each element of this grid corresponds to a specific point (x,y) in the region scanned and is filled with one colour. All elements of the grid representing one particular cluster are assigned a single colour. It is observed that the damage zone is well defined in the plot of peak amplitude compared to the plots of harmonics. Since the plate is having impacted damage it is expected that the damage is dominated by delaminations. It has been reported earlier that for delamination peak amplitudes attenuate significantly in through transmission. However the other types of damages in impact loading such as fibre fracture and matrix cracking, cannot be detected efficiently with this method. Another main disadvantage of this method lies in the fact that both the sides of the object must be amenable, which is rarely met in real situations. Hence *Pulse Echo Method* was investigated in the following analysis.

5.5 RESULTS OF PULSE ECHO SCANS

The normal beam pulse echo scanning was carried on both glass/epoxy and graphite/epoxy laminates. The same impacted laminate used in the through transmission method

was rescanned using pulse echo technique. A 4 MHz transducer(ENM4L) was used for scanning.

Initially the scan was carried out to obtain peak amplitude and the full wave data. The full waves were analysed using FFT analysis to obtain harmonics. The plot of peak amplitude is shown in fig. 5.2 (P2) and those of the harmonics are shown in fig. 5.3 (Second row). The plot of clustered output for peak amplitude shows a pattern in the damage area. The plots of harmonics also show some indication of the damage area. Since the first five harmonics are not having clear patterns, it was decided to go for higher harmonics. The results of higher harmonics for this laminate have been discussed in subsequent sections. Also after repeating the experiment a few times the following observations have been made,

1. Probes with smaller crystal diameter will reduce beam divergence,

2. Plot of higher frequency components will give better image,

Since small diameter probes and focusing lenses were not available at present, the probe of 10 MM diameter was covered with rubber mask and a small hole of 3 MM diameter was made at the center. To compensate for the loss of energy the intensity of the transmitted signal was increased. It was found that temporal averaging of the full wave data was not possible as the wave was not very stable with time and did not yield good results. Hence it was decided to do an online FFT of the data collected at each point several times (5) and averages of the components thus obtained were recorded. The clustered output of the peak amplitude is shown in fig. 5.2 (P3). The plots of the 50 harmonics are as shown in figs. 5.4 to 5.8. The plots in the frequency range of 1.1 to 3.5 MHz are showing some pattern in the damage area. Since the higher frequency components of the signal are of smaller wavelengths, the interaction of these components extract better information

about the damage zone which is clearly seen in these photographs. However as the frequency increases the attenuation of the wave due to scattering increases rapidly as scattering is directly proportional to the fourth power of the former. Hence the frequency component of the wave above certain frequency range may not be able to extract better information.

The Hierarchical Clustering can be done with one or more variables at a time. The Clustered output of more than one variables combined is expected to be better than the clustered output of the individual variable. For this, a systematic approach was adopted for finding a better combination of variables. The following steps describe the process of combination of different variables. For the model experiment, the selected specimens contained some portion of clearly visible damaged region. For the boundary of the damaged region the coordinates of the points describing the boundary were determined (i.e., for any X-coordinate , Y-max & Y-min were determined on the boundary of the damaged region).

In the next step, effectiveness of each clustered output to discriminate the region is proposed to be determined by determining a quantity, effective index (say Wt). In any clustered output Wt will be high, if the damage region is populated by clusters which are predominantly present or absent.

The effectiveness index of the harmonic is calculated as

$$Wt_i = abs(\frac{c_i}{n_i} - \frac{c_o}{n_o}) \times 100. \tag{5.1}$$

where

c_i = number of points in the specified region identified by cluster i.

c_o = number of points outside the specified region identified by cluster i.

n_i = total number of points inside the specified region.

n_o = total number of points outside the specified region.

The total effectiveness of the clustering of the particular harmonic is given by

$$Wt = (\sum_{i=1}^{n} Wt_i) \tag{5.2}$$

Such exercise can also be done on the clustering with more than one variable. A systamatic sequential combination of variables is done as shown in the flow chart as shown in fig.5.1 The plots of the frequency components combined and clustered are as shown in fig. 5.9. The plots are clear in identifying the damage zone and support the observations made earlier.

The above procedure was repeated on another Glass/epoxy laminate with 6MHz (EI6B) broad band probe of 10MM diameter. The peak amplitude plot is as shown in fig. 5.2 (P4). The plot of frequency components clustered individually are shown in figs. 5.10 to 5.14. The frequency components showing the region of damage were combined and clustered. The plots are shown in fig. 5.15. It is seen that the broad band probe gives better information in the frequency domain. This is due to the fact that the broad band probe have a large number of frequencies of sufficient strength and decomposing the echo signal into individual components is equivalent to getting response from probes of different frequencies.

5.6 RESULT OF SCAN ON GRAPHITE/EPOXY PLATES

Two impact damaged Graphite/Epoxy composite laminates were scanned using a 4MHz (ENM4L) probe. The results are shown in figs. 5.16 to 5.20. The plots of frequency components do not contain much information about the damage zone. The same specimen was again scanned with 6 MHz broad band (EI6B) probe and the results are shown in fig. 5.21 to fig. 5.25. It is observed that the broad band probe gives better results than the 4MHz resonant probe.

The same EI6B probe was used to scan another Graphite/Epoxy laminate. The plots are shown in figs. 5.26 to 5.30. The plots show that damages in that damages in the specimen are more sensitive to the frequency components and a very clear region of damage can be seen. From this it can be inferred that a wide range of probes in the frequency range below 10 MHz have to be used before standardizing the required probe for scanning the composite plates. It has been reported in literature [25] that when frequencies below 10 MHz are used the composite materials can be assumed to be homogeneous.

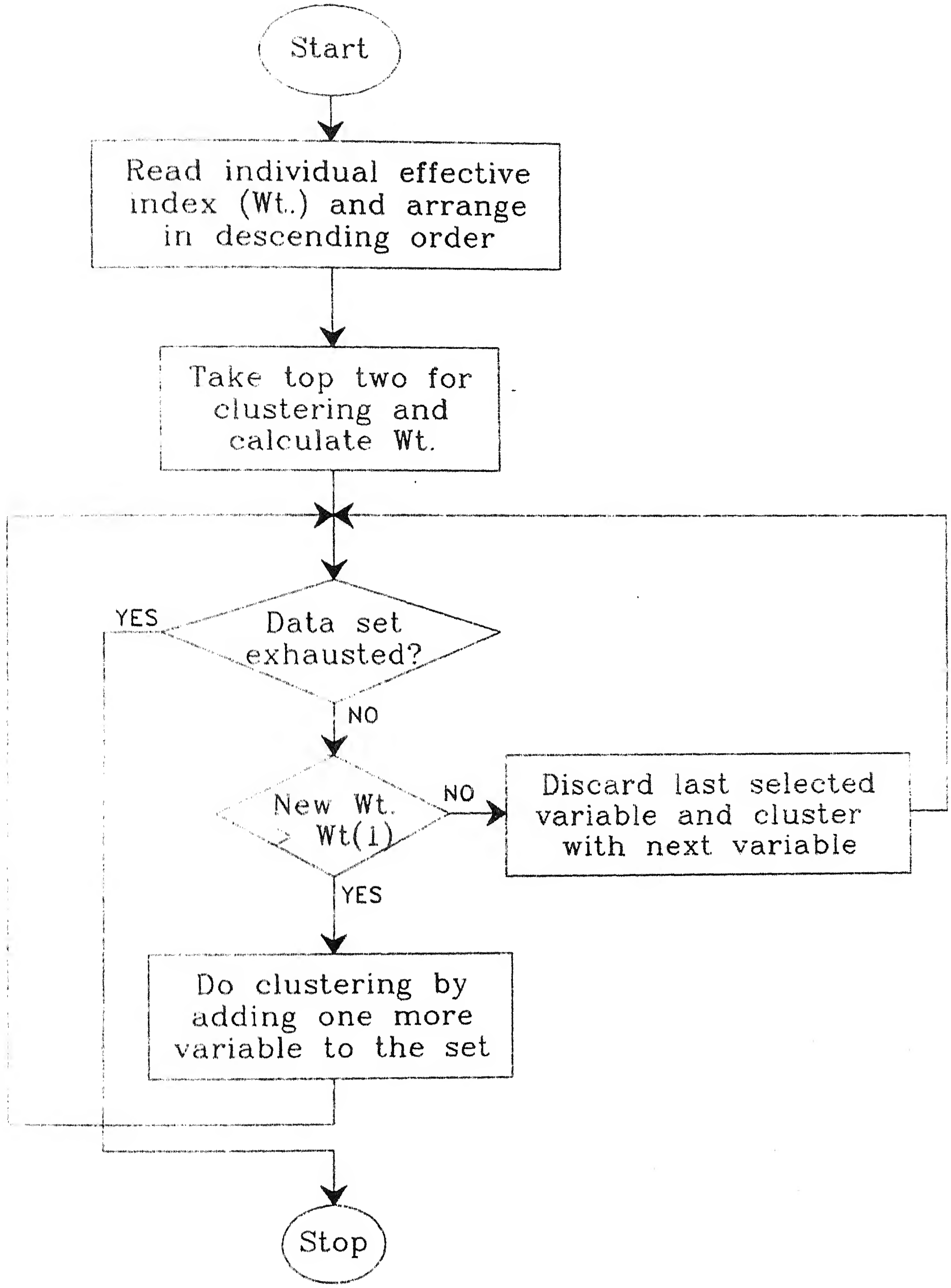

Figure 5.1: Flowchart for Sequential Combination of Variables

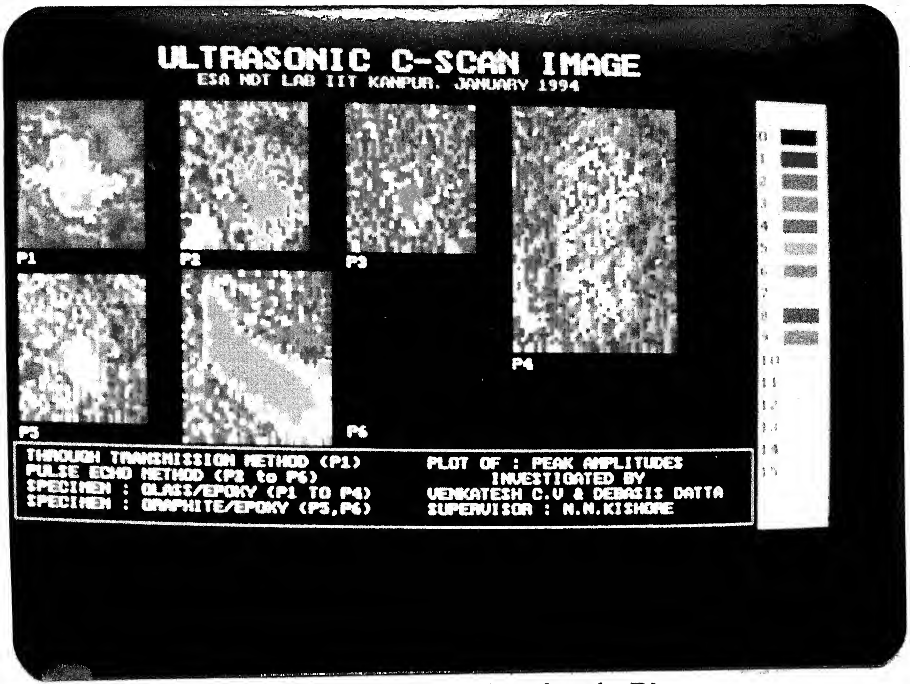

Figure 5.2: Peak Amplitude Plots

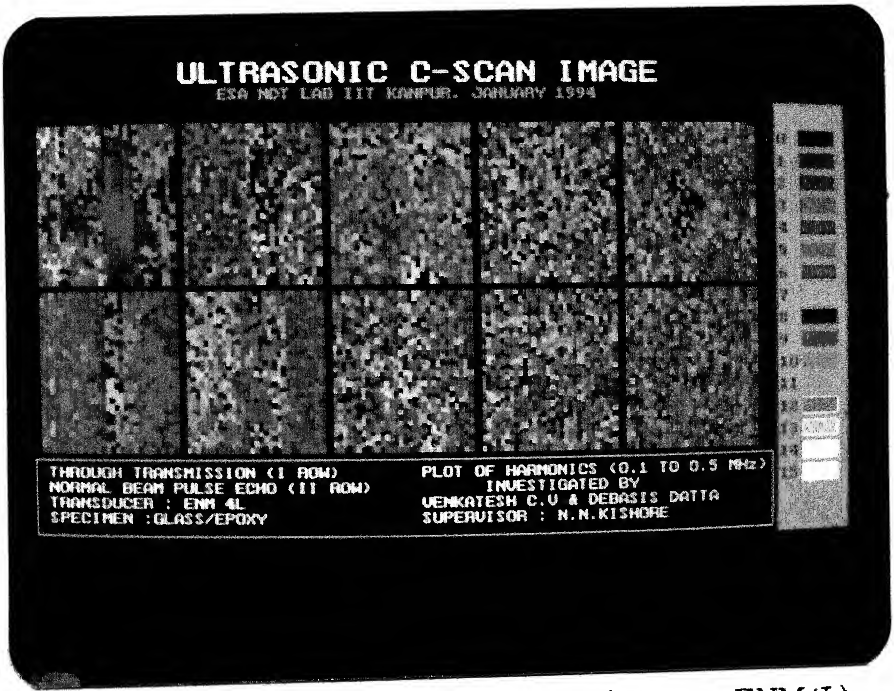

Figure 5.3: First Five Harmonics (Glass/epoxy 1; ENM4L)

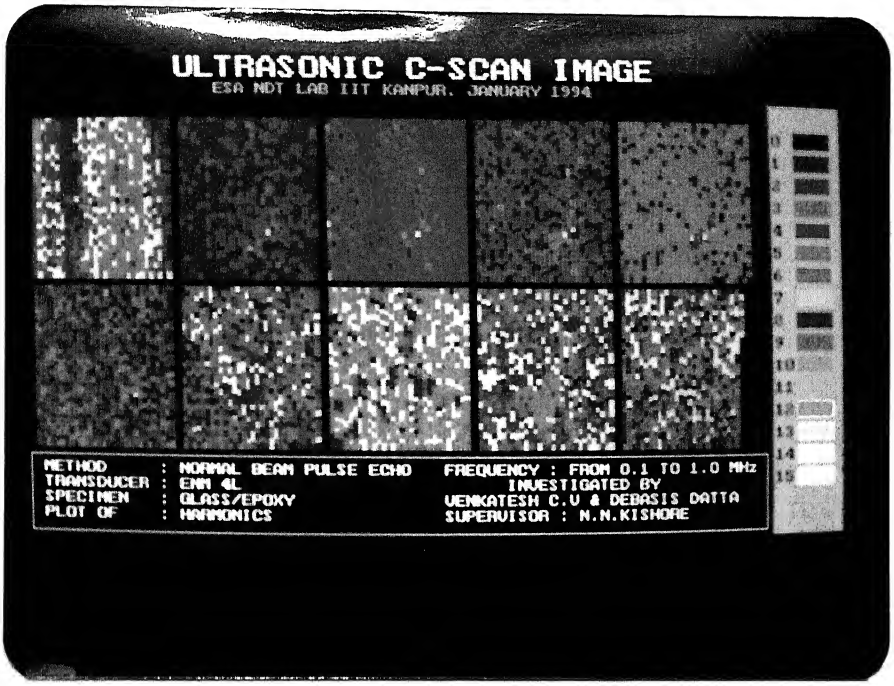

Figure 5.4: Harmonics 1 to 10 (Glass/epoxy 1; ENM4L)

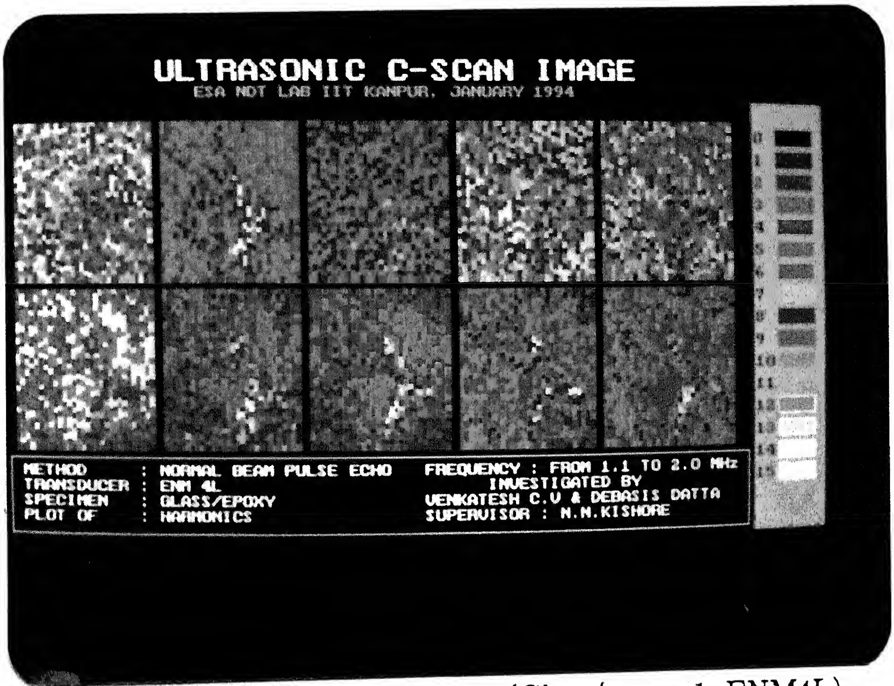

Figure 5.5: Harmonics 11 to 20 (Glass/epoxy 1; ENM4L)

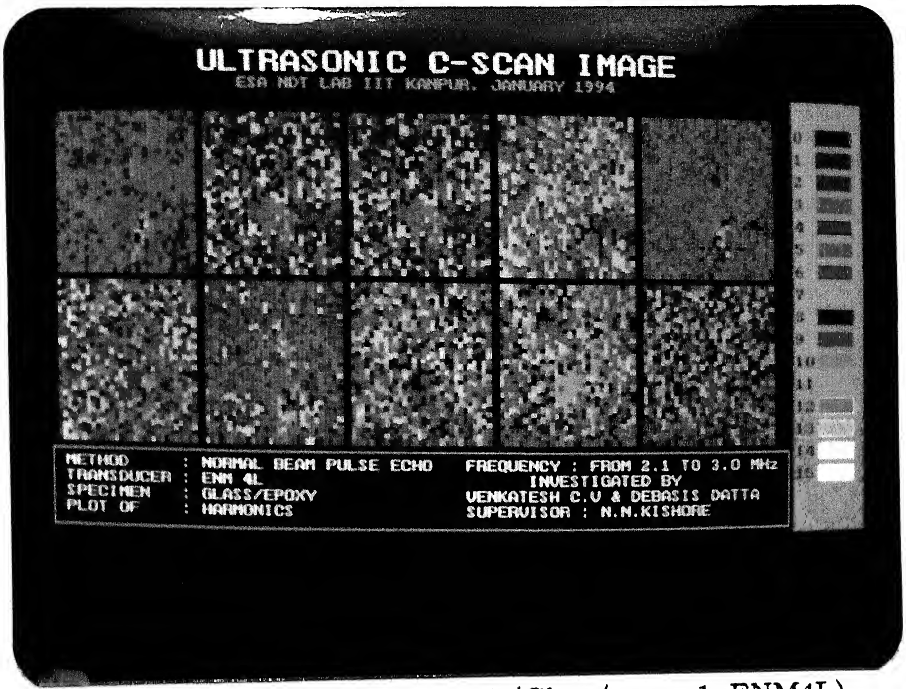

Figure 5.6: Harmonics 21 to 30 (Glass/epoxy 1; ENM4L)

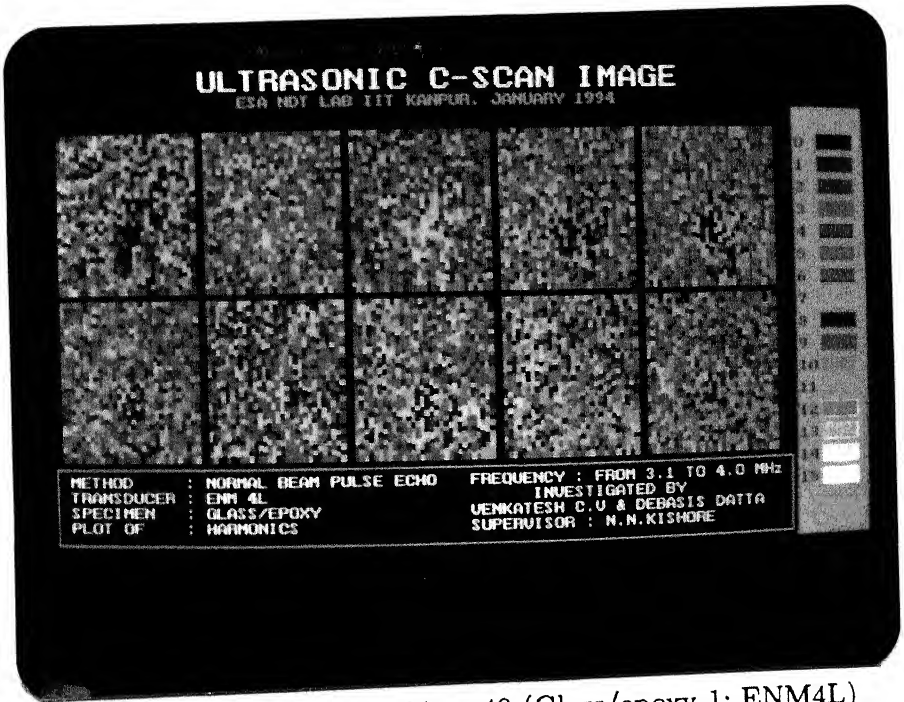

Figure 5.7: Harmonics 31 to 40 (Glass/epoxy 1; ENM4L)

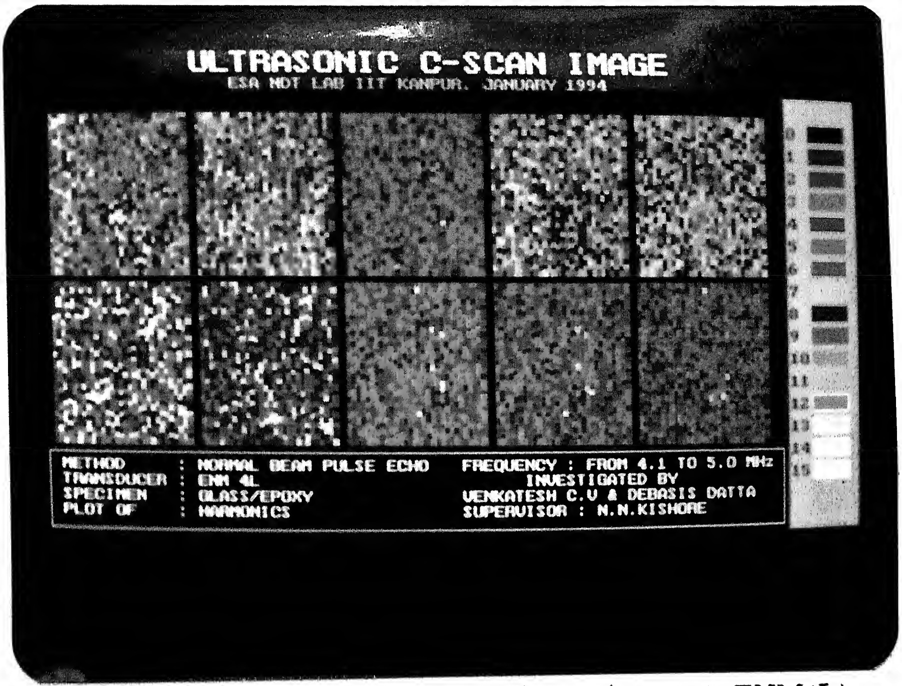

Figure 5.8: Harmonics 41 to 50 (Glass/epoxy 1; ENM4L)

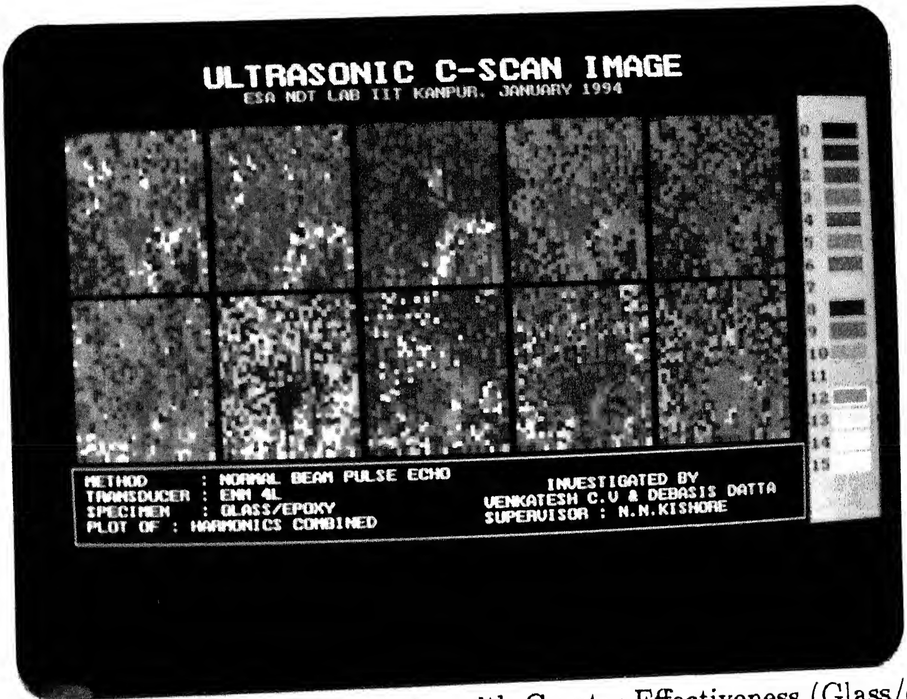

Figure 5.9: Combinations of Harmonics with Greater Effectiveness (Glass/epoxy 1; ENM4L)

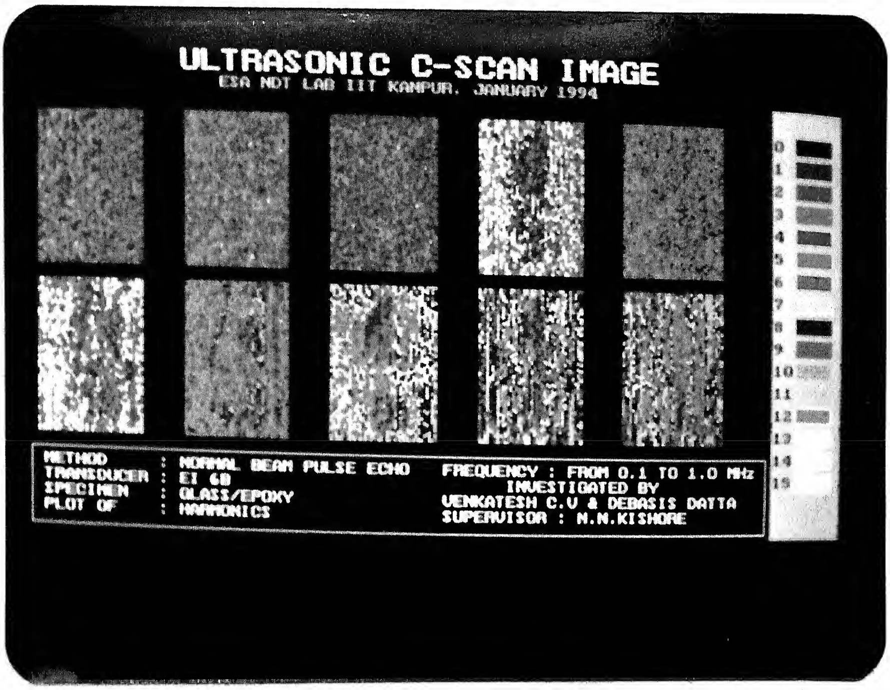

Figure 5.10: Harmonics 1 to 10 (Glass/epoxy 2; EI6B)

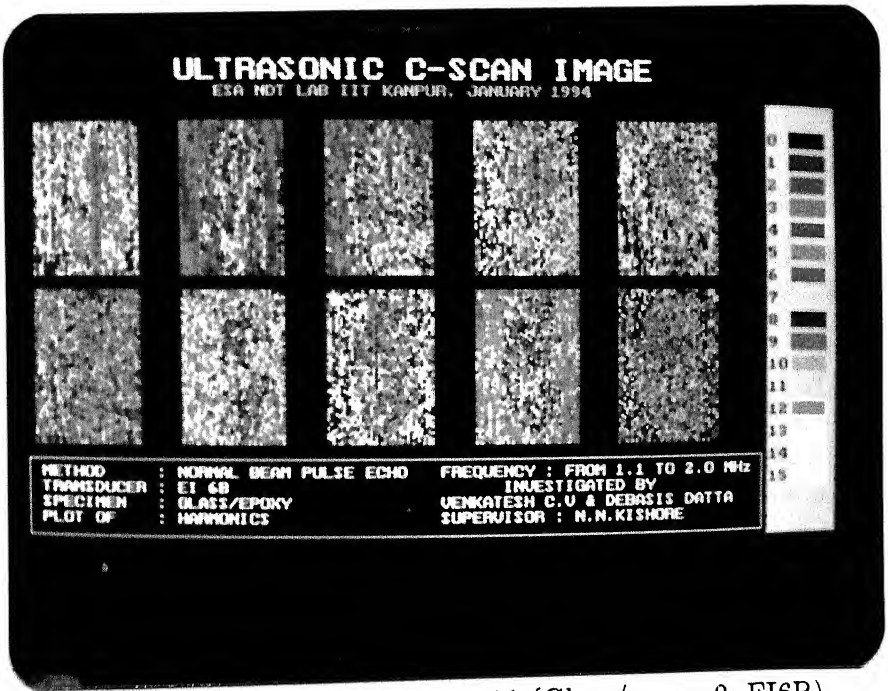

Figure 5.11: Harmonics 11 to 20 (Glass/epoxy 2; EI6B)

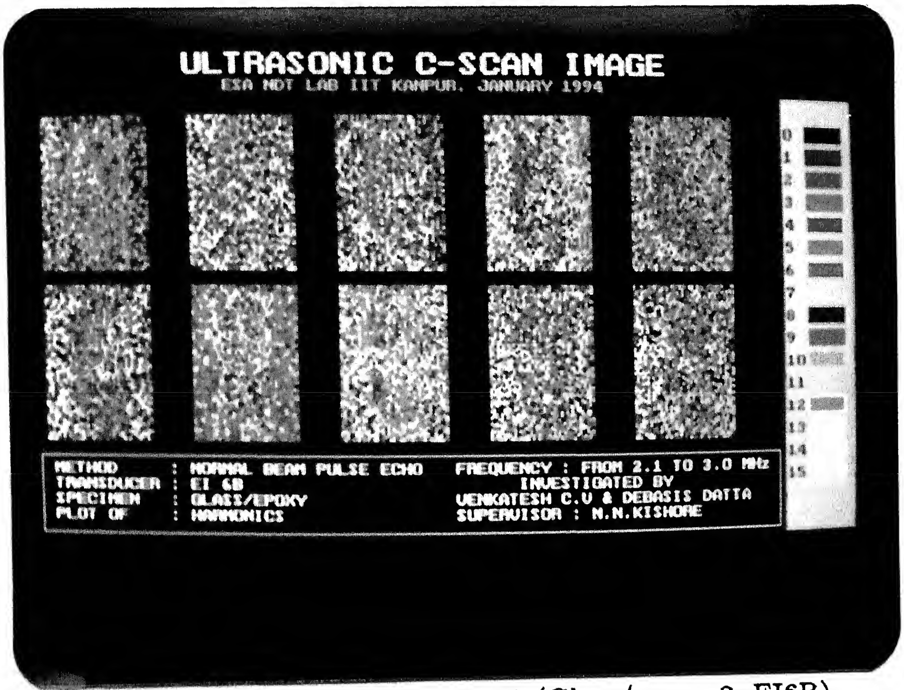

Figure 5.12: Harmonics 21 to 30 (Glass/epoxy 2; EI6B)

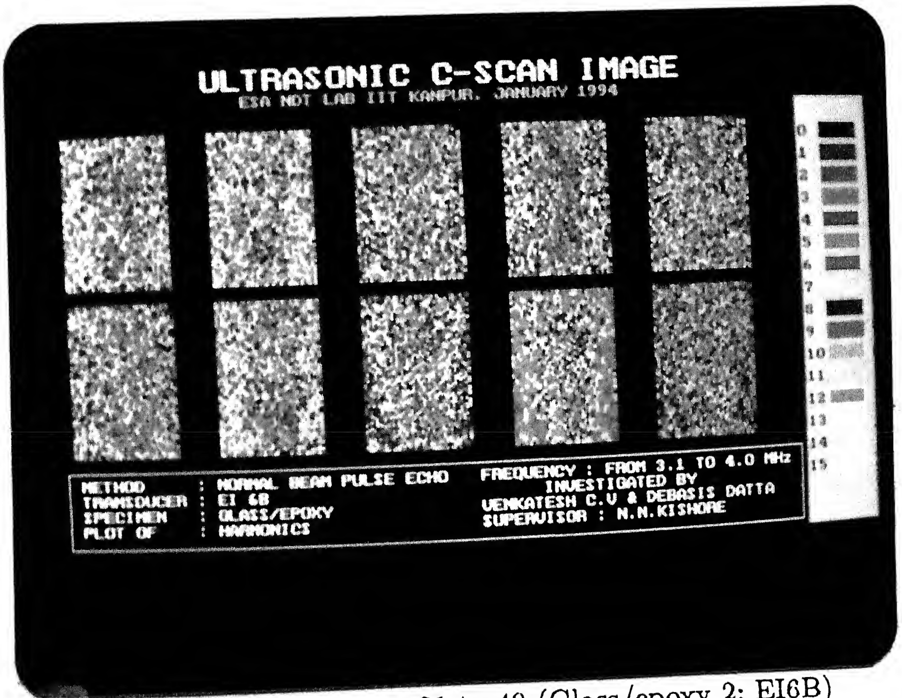

Figure 5.13: Harmonics 31 to 40 (Glass/epoxy 2; EI6B)

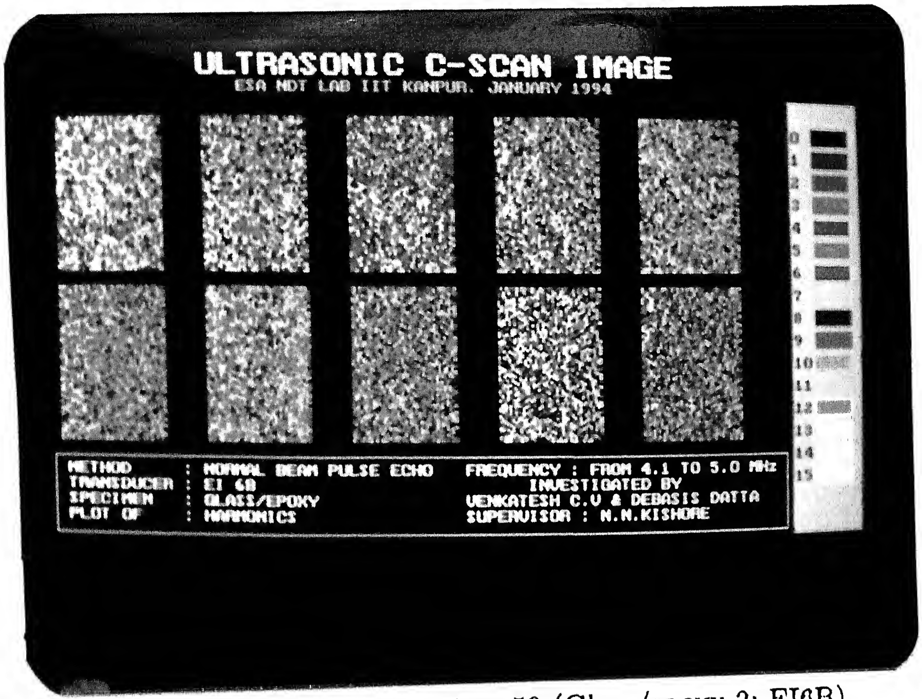

Figure 5.14: Harmonics 41 to 50 (Glass/epoxy 2; EI6B)

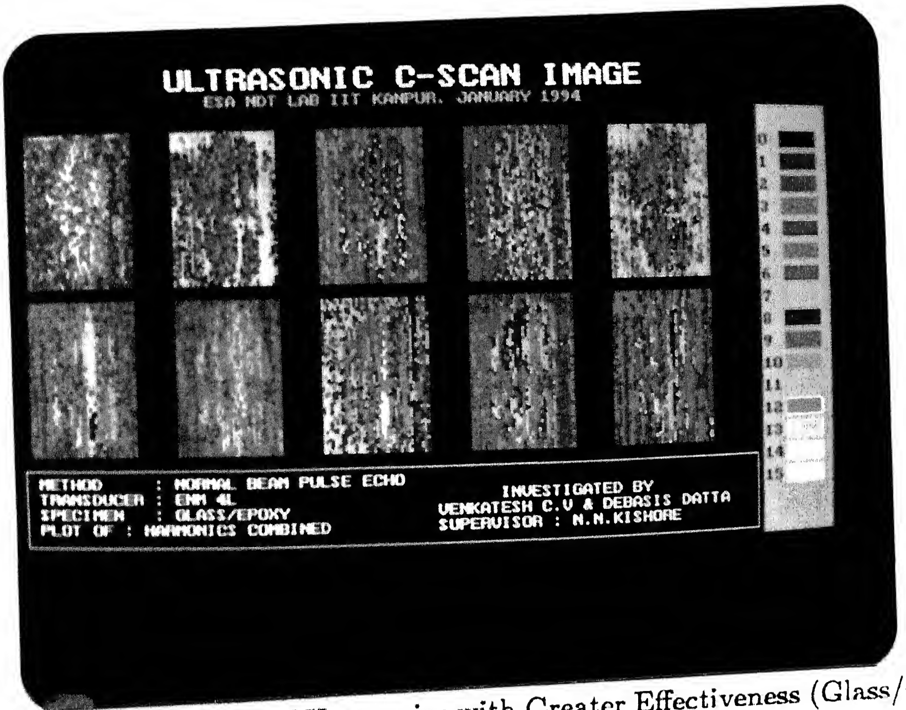

Figure 5.15: Combination of Harmonics with Greater Effectiveness (Glass/epoxy 2; EI6B)

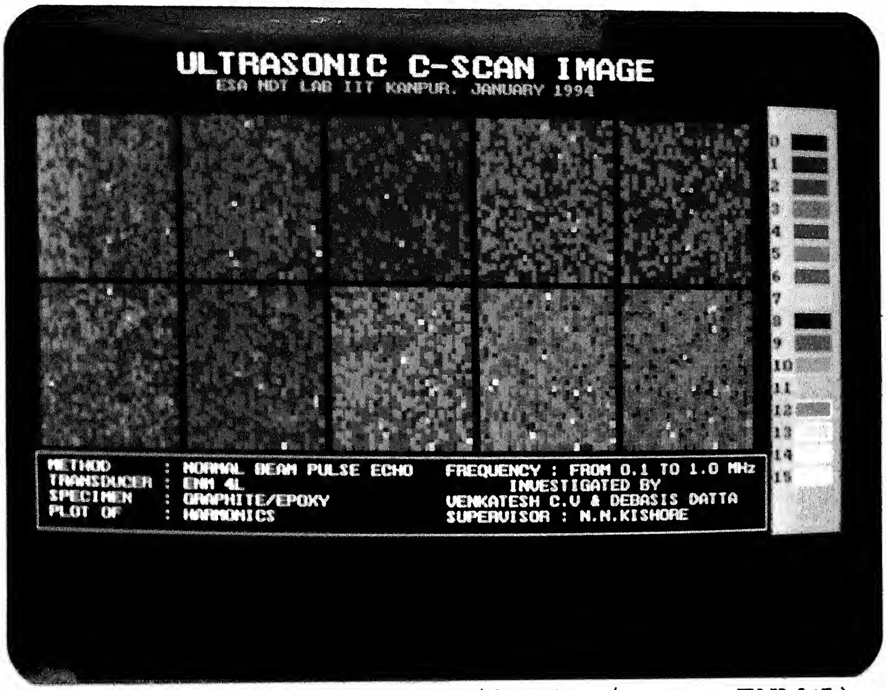

Figure 5.16: Harmonics 1 to 10 (Graphite/epoxy 1; ENM4L)

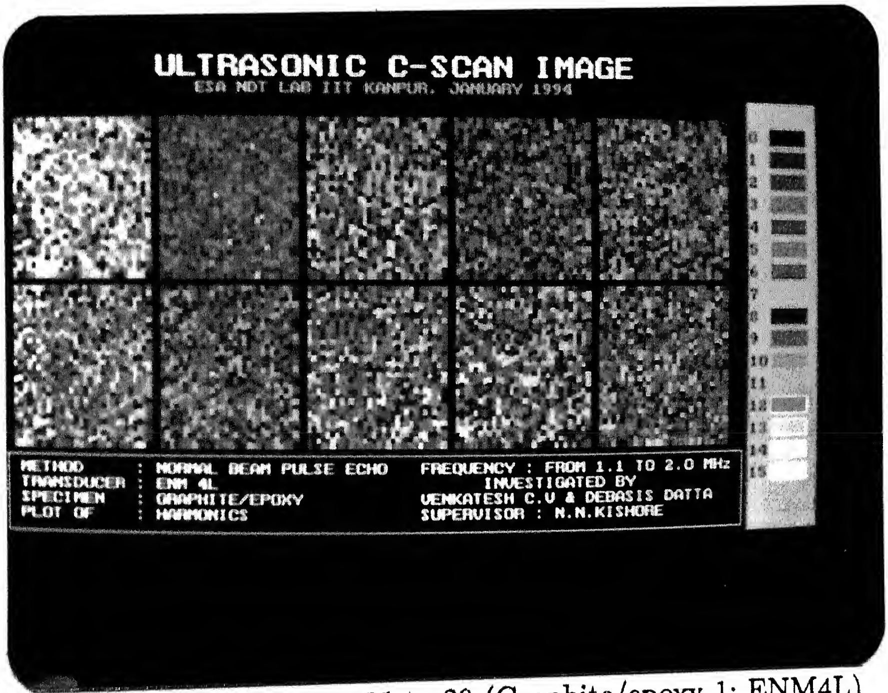

Figure 5.17: Harmonics 11 to 20 (Graphite/epoxy 1; ENM4L)

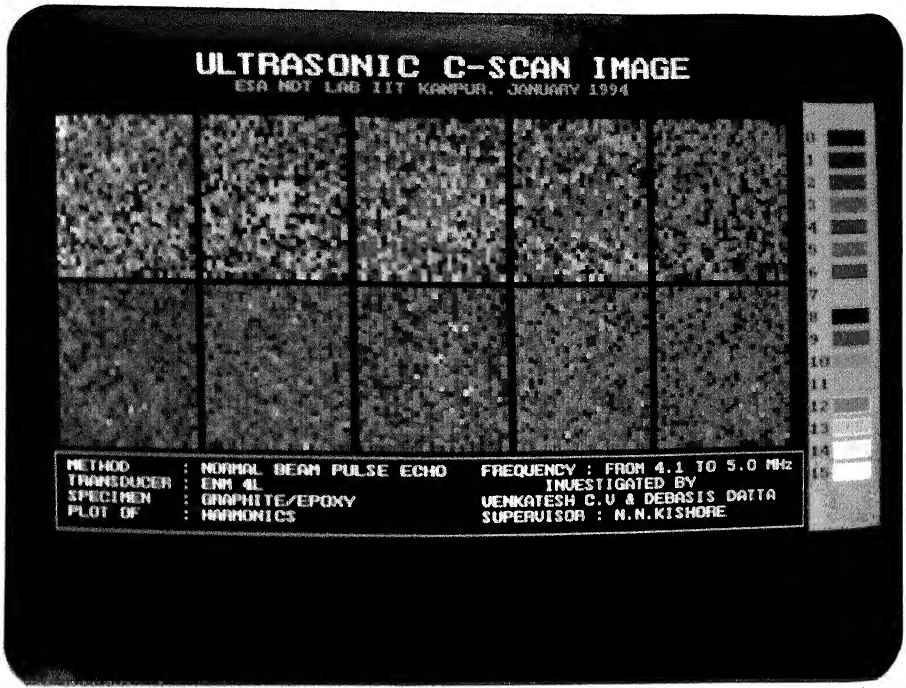

Figure 5.20: Harmonics 41 to 50 (Graphite/epoxy 1; ENM4L)

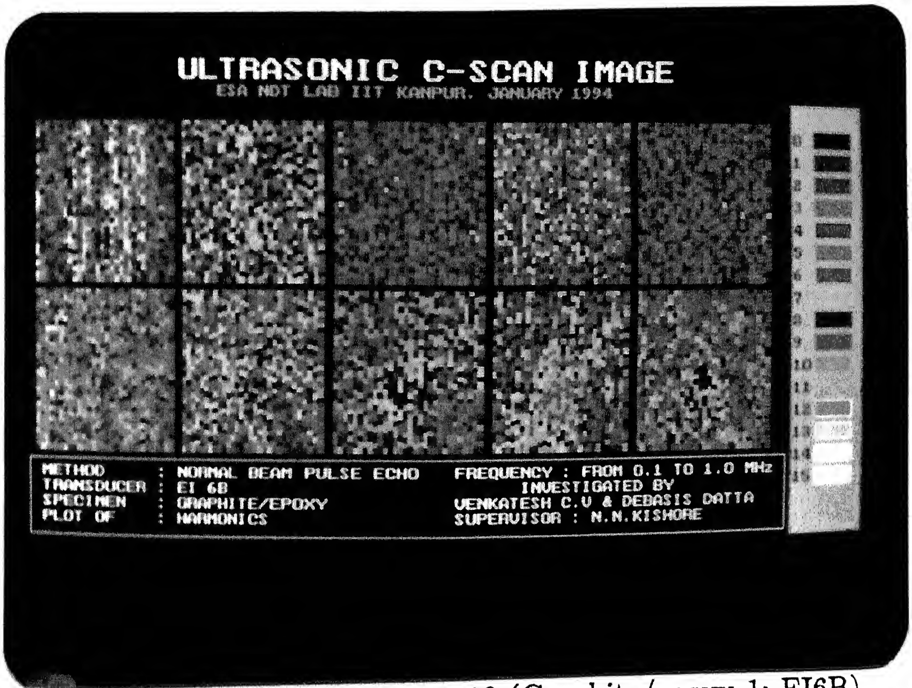

Figure 5.21: Harmonics 1 to 10 (Graphite/epoxy 1; EI6B)

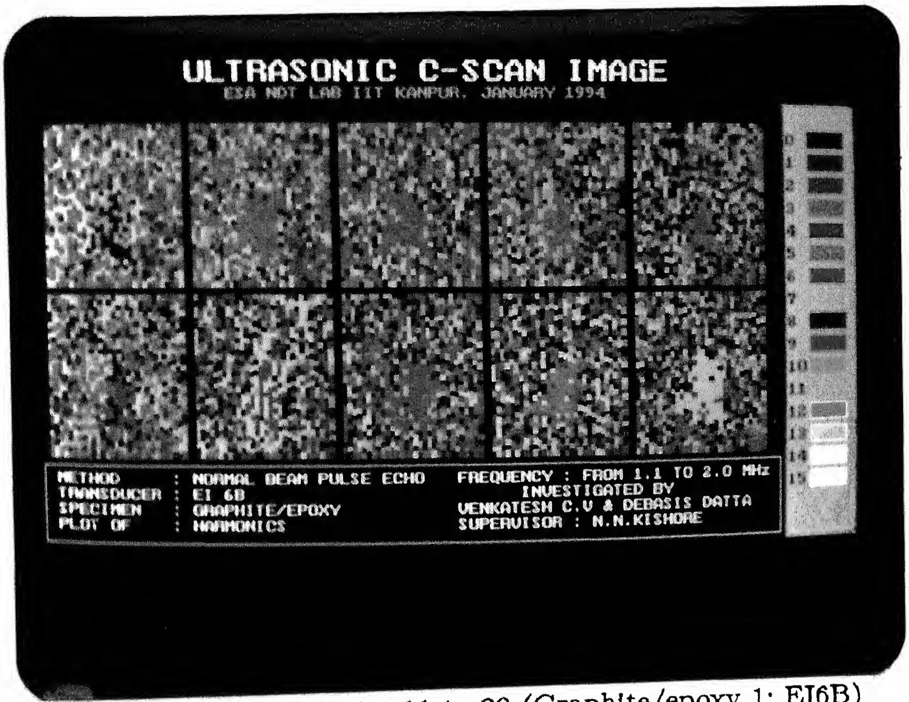

Figure 5.22: Harmonics 11 to 20 (Graphite/epoxy 1; EI6B)

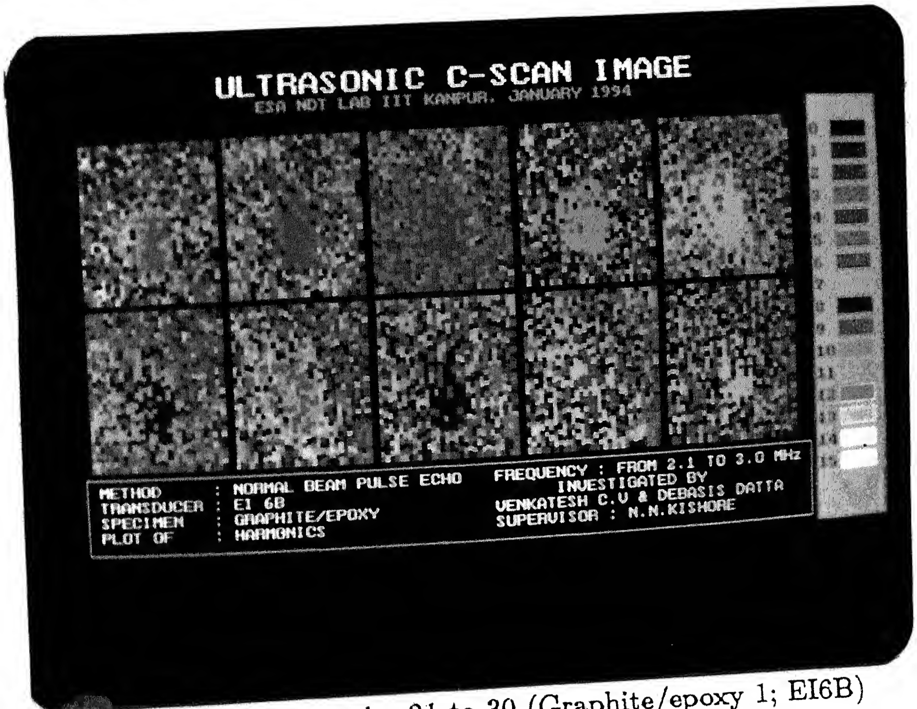

Figure 5.23: Harmonics 21 to 30 (Graphite/epoxy 1; EI6B)

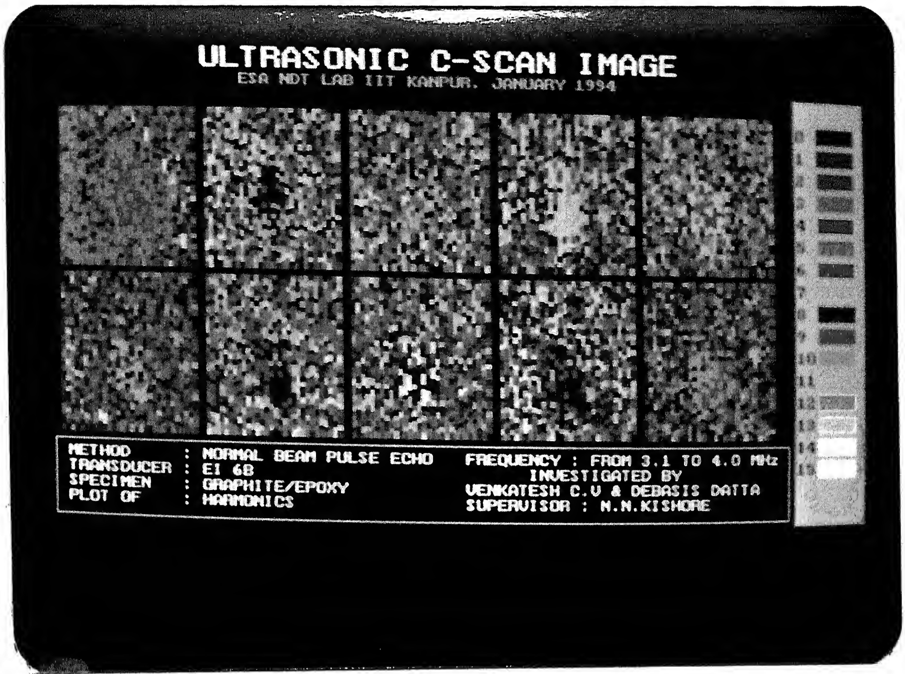

Figure 5.24: Harmonics 31 to 40 (Graphite/epoxy 1; EI6B)

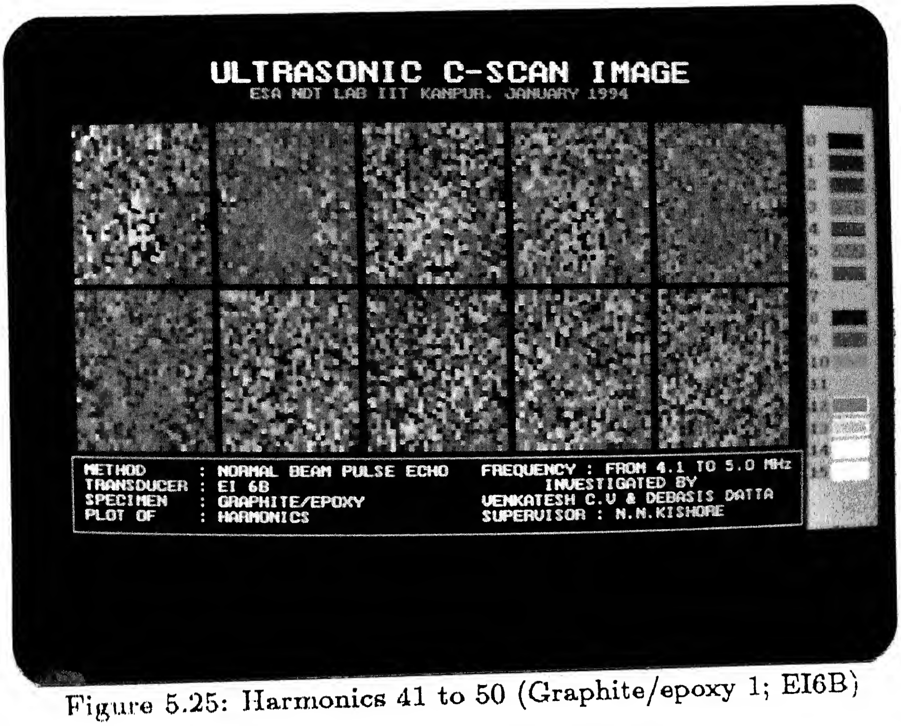

Figure 5.25: Harmonics 41 to 50 (Graphite/epoxy 1; EI6B)

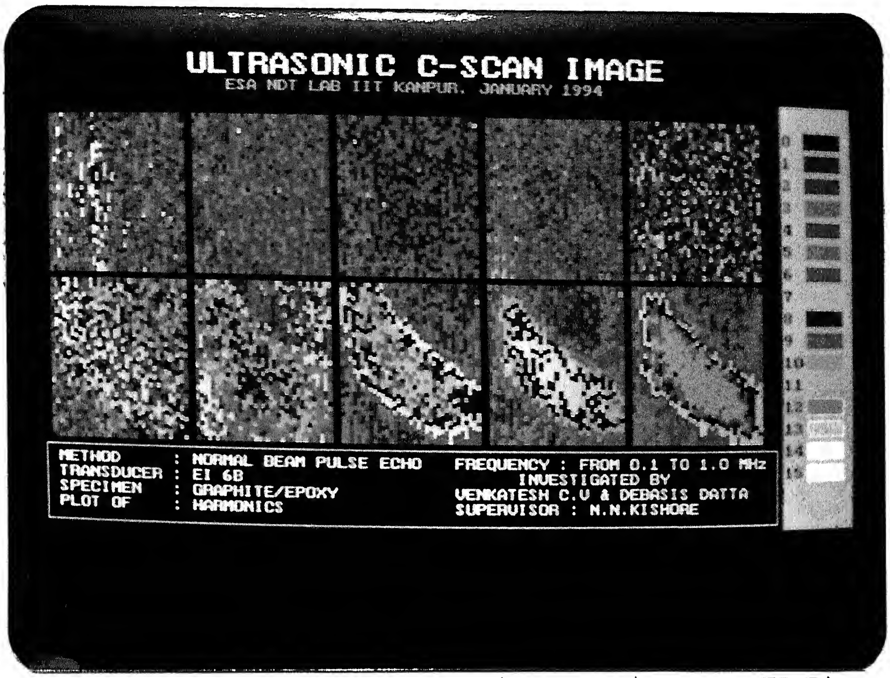

Figure 5.26: Harmonics 1 to 10 (Graphite/epoxy 2; EI6B)

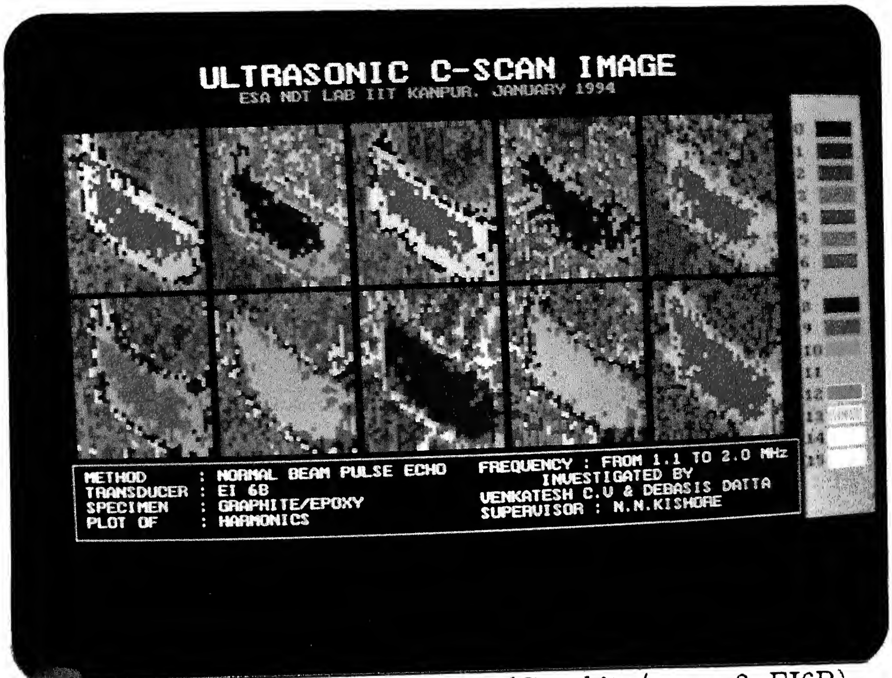

Figure 5.27: Harmonics 11 to 20 (Graphite/epoxy 2; EI6B)

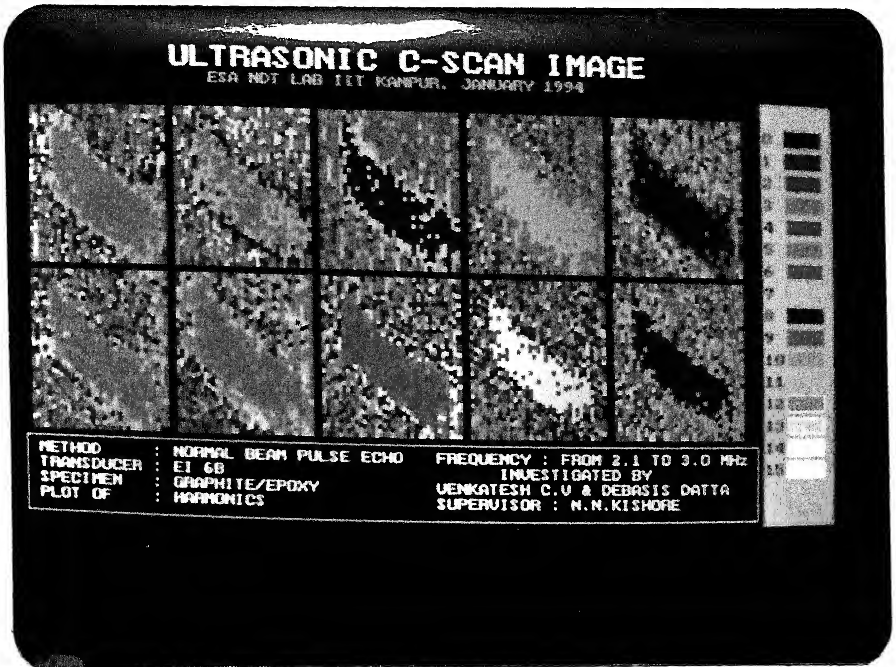

Figure 5.28: Harmonics 21 to 30 (Graphite/epoxy 2; EI6B)

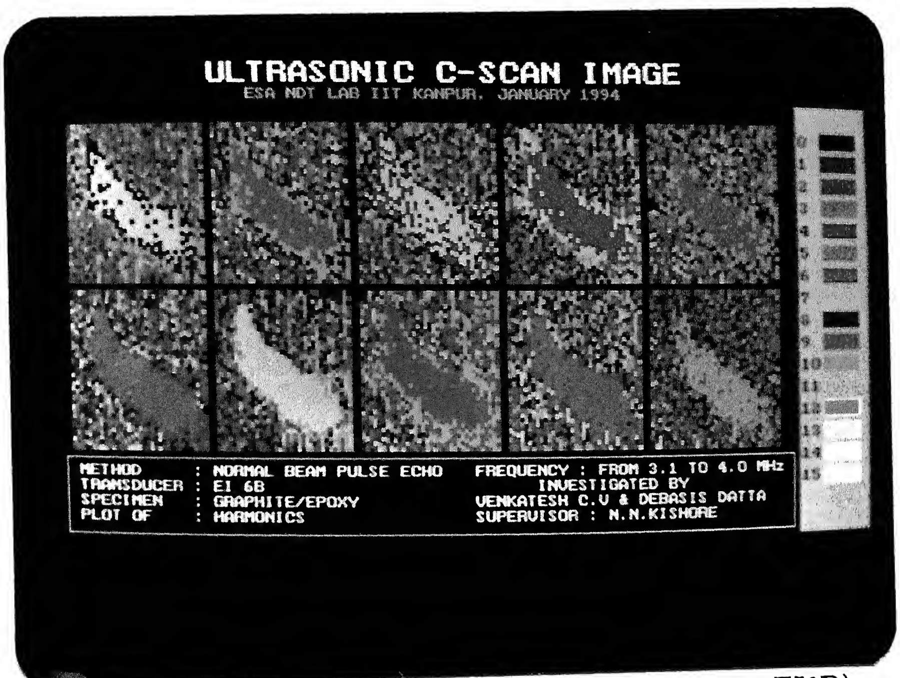

Figure 5.29: Harmonics 31 to 40 (Graphite/epoxy 2; EI6B)

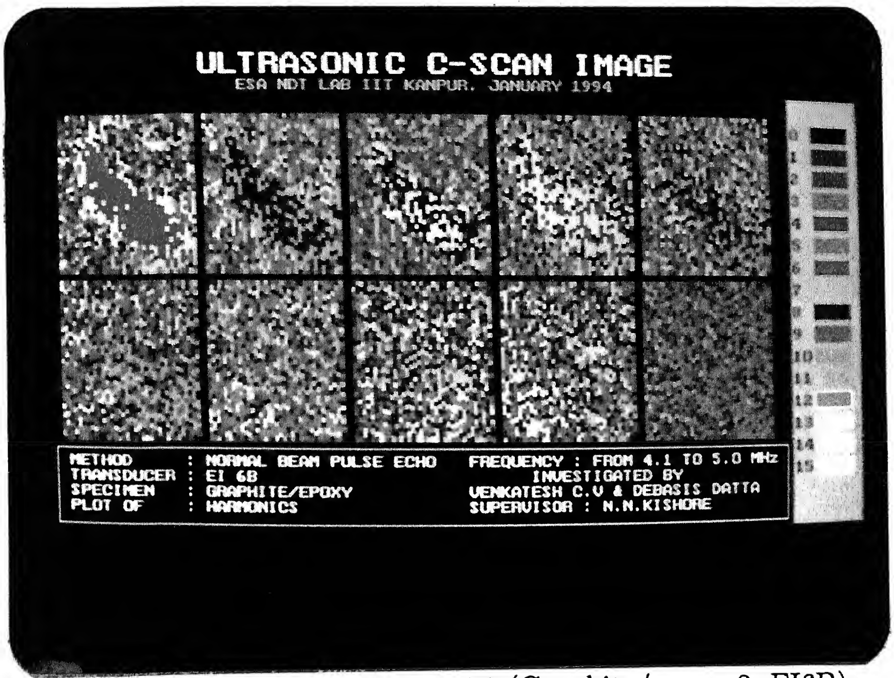

Figure 5.30: Harmonics 41 to 50 (Graphite/epoxy 2; EI6B)

Chapter 6

CONCLUSIONS AND SCOPE FOR FUTURE WORK

6.1 CONCLUSIONS

In the present work, a PC-AT based ultrasonic inspection system was developed using an available mechanized scanner to generate C-scan images based on the peak amplitude and frequency components of the received signals. For this purpose, an ultrasonic flaw detector and scanning setup were interfaced with a PC-AT through an A/D converter. The softwares for precise motion of motor and for collection of full wave data were developed. Softwares were also developed for post processing of the collected data. Hierarchical clustering method was used for processing of the data. The C-scan images of the scanned regions were plotted by assigning different colours to the different groups of clusters obtained. The damage zones were identified in composite laminates.

Model experiments were conducted on Glass/epoxy and Graphite/epoxy laminates with visible impact damages. The scan was taken for three more specimens.

The scanning programs were modified to get an online FFT of the data collected.

From the results discussed in chapter 5, it can be concluded that, the present system (hardware and software) can be effectively used for identification of the damage zones. It facilitates the collection of large volumes of data for post processing. The system can be employed to damage identification and analysis of failures in composite laminates subjected to destructive tests.

6.2 SCOPE FOR FUTURE WORK

1. Broad band probes may be used to get more accurate information on harmonics.
2. Focussed small diameter probes may be used to concentrate the transmitted signal upon a small region to reduce beam divergence.
3. Composite laminates with known flaws like inserts may be used to get more information on the effect of these flaws on harmonics.
4. Phase information of the harmonics may be collected and analysed.
5. Fixtures may be fabricated for fixing the plates very accurately while scanning.

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